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(54) **METHOD FOR MAKING MEASUREMENTS OF THE POST-COMBUSTION RESIDENCE TIME IN A GAS TURBINE ENGINE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 513 days.

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(51) **Int. Cl.**
F01D 21/04	(2006.01)
G01M 15/14	(2006.01)
F01D 21/00	(2006.01)

(52) **U.S. Cl.**
CPC **G01M 15/14** (2013.01); **F01D 21/003** (2013.01)

(58) **Field of Classification Search**
CPC F01D 21/003; G01M 15/14
USPC 73/112.01, 865.9, 701, 702
See application file for complete search history.

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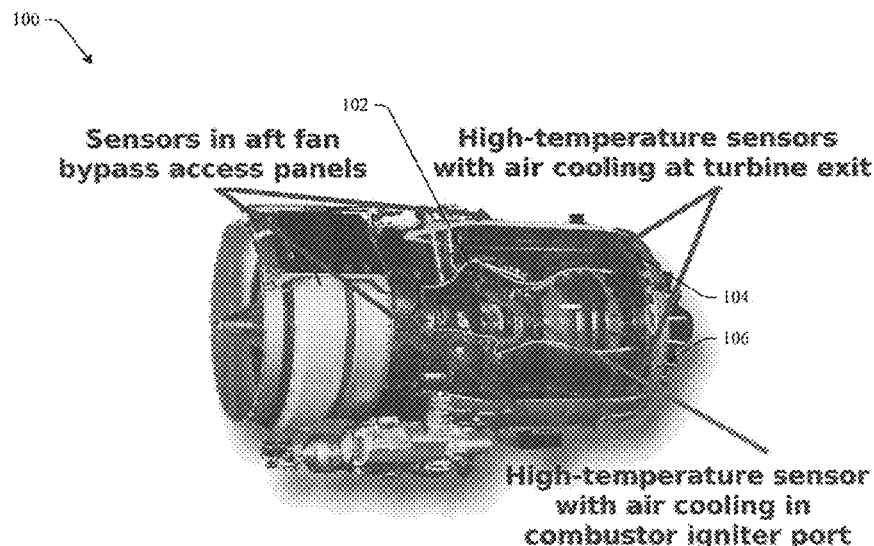* cited by examiner

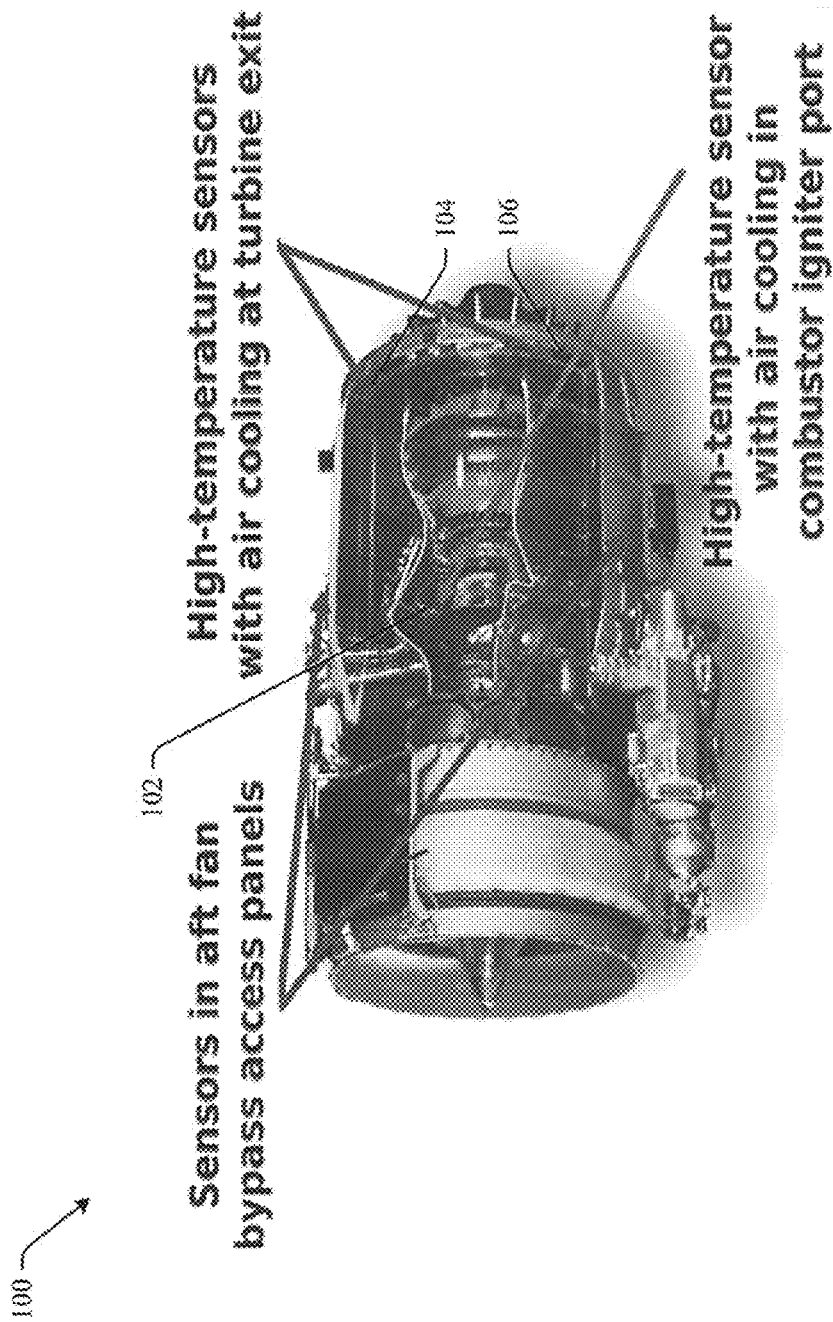*Primary Examiner* — Lisa Caputo
Assistant Examiner — Nigel Plumb
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(57) **ABSTRACT**

A system and method of measuring a residence time in a gas-turbine engine is provided, whereby the method includes placing pressure sensors at a combustor entrance and at a turbine exit of the gas-turbine engine and measuring a combustor pressure at the combustor entrance and a turbine exit pressure at the turbine exit. The method further includes computing cross-spectrum functions between a combustor pressure sensor signal from the measured combustor pressure and a turbine exit pressure sensor signal from the measured turbine exit pressure, applying a linear curve fit to the cross-spectrum functions, and computing a post-combustion residence time from the linear curve fit.

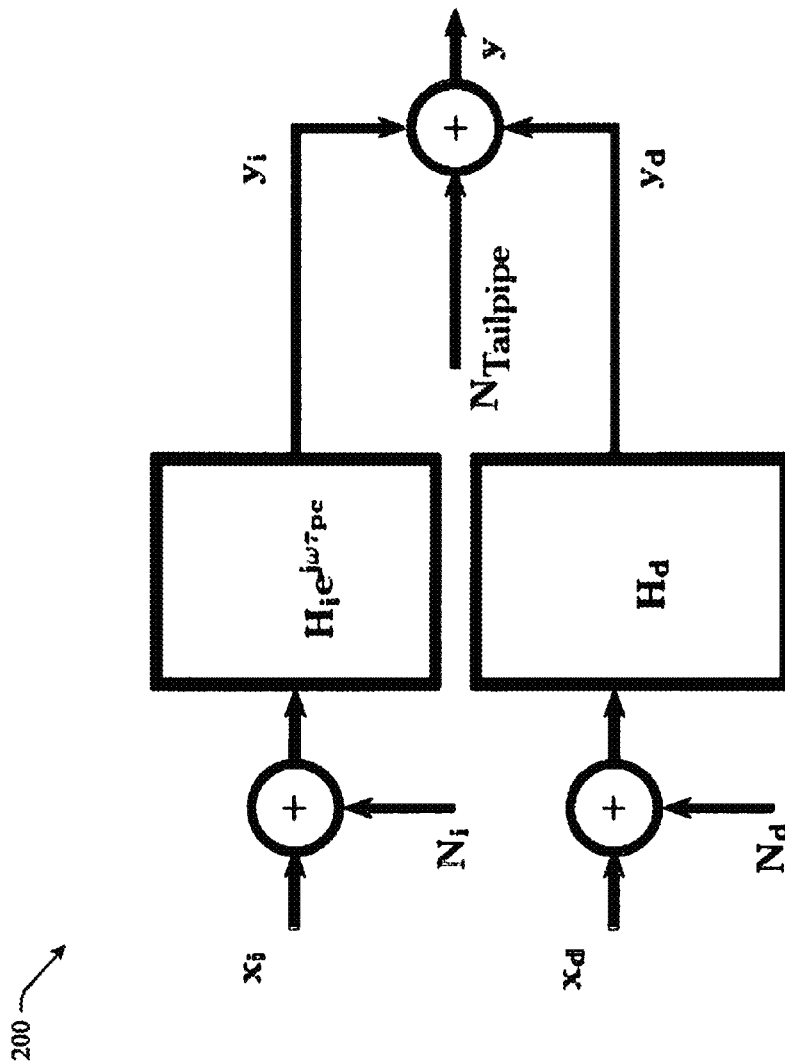**20 Claims, 20 Drawing Sheets**

100

102

Sensors in aft fan bypass access panels

High-temperature sensors with air cooling at turbine exit

104

106

High-temperature sensor with air cooling in combustor igniter port

High-temperature sensors
with air cooling at turbine exit

High-temperature sensor
with air cooling in
combustor igniter port

Sensors in aft fan
bypass access panels

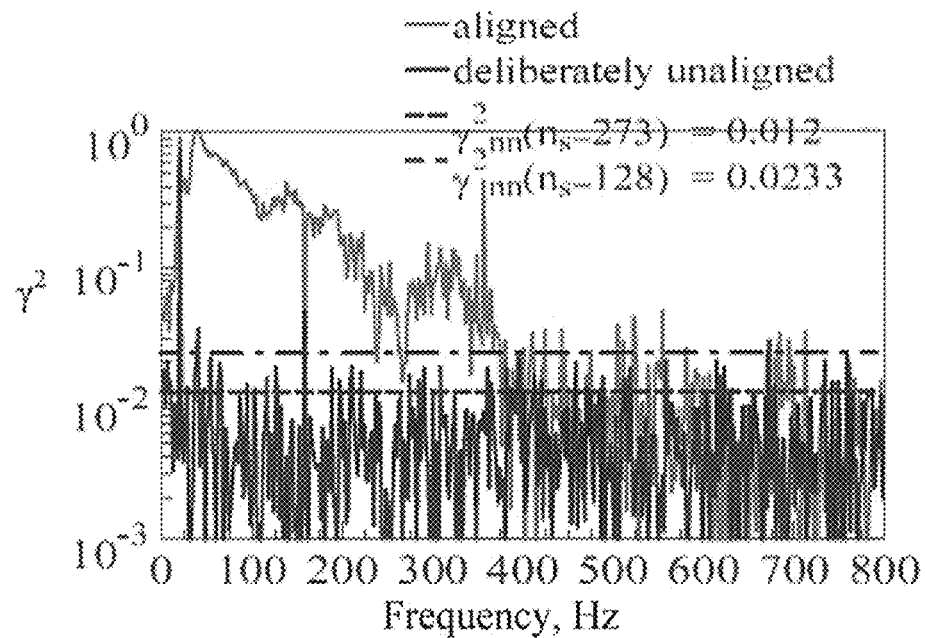104

106

102

100

FIG. 1

FIG. 2
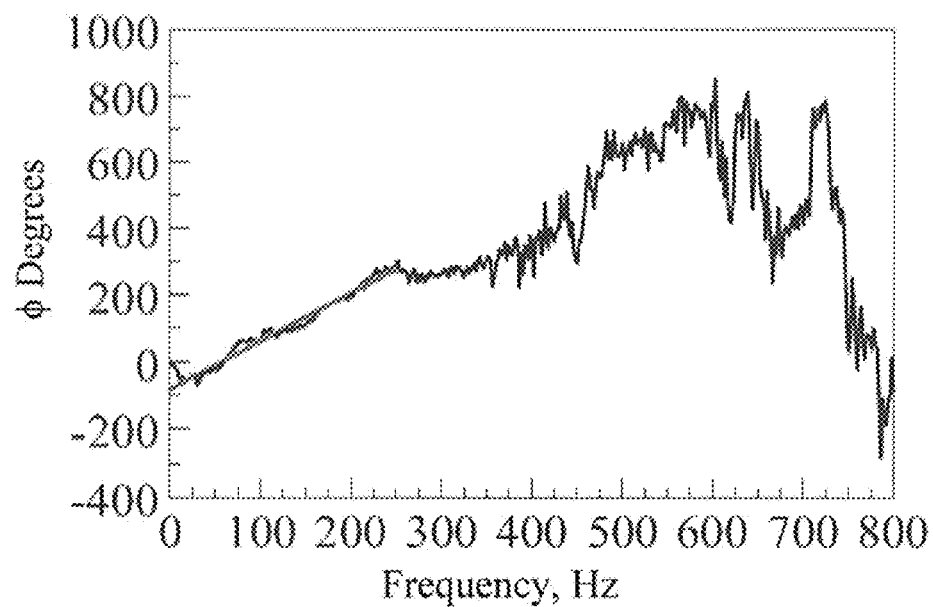
FIG. 3A - Coherence

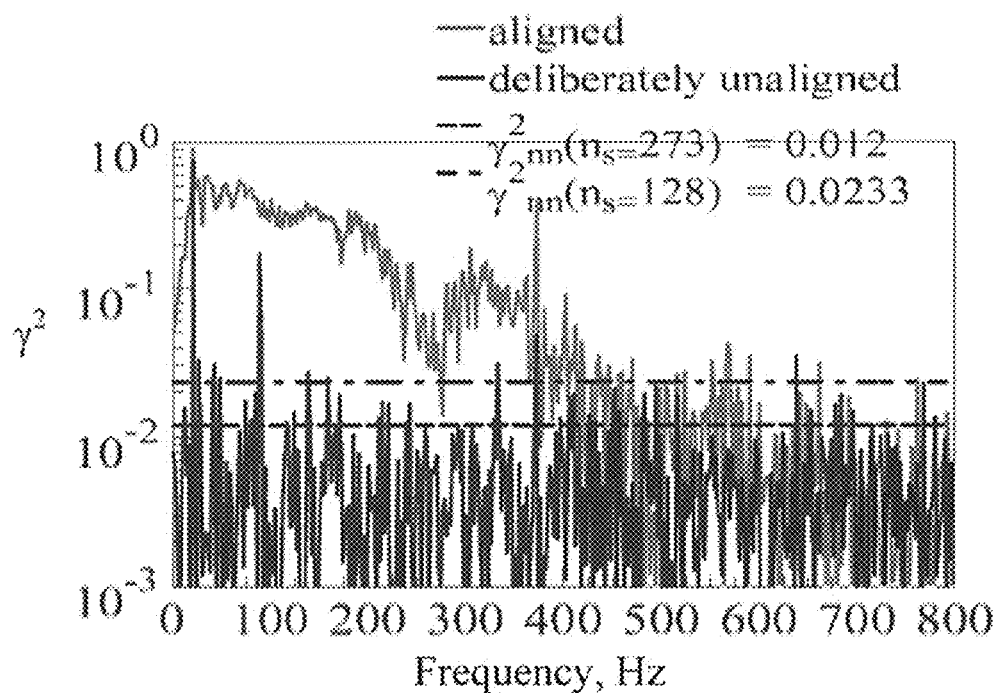

FIG. 3B – Cross-Spectrum Phase angle

FIG. 4A - Coherence

FIG. 4B – Cross-Spectrum Phase angle

FIG. 5A - Coherence

FIG. 5B – Cross-Spectrum Phase angle

FIG. 6A - Coherence

FIG. 6B – Cross-Spectrum Phase angle

FIG. 7A - Coherence
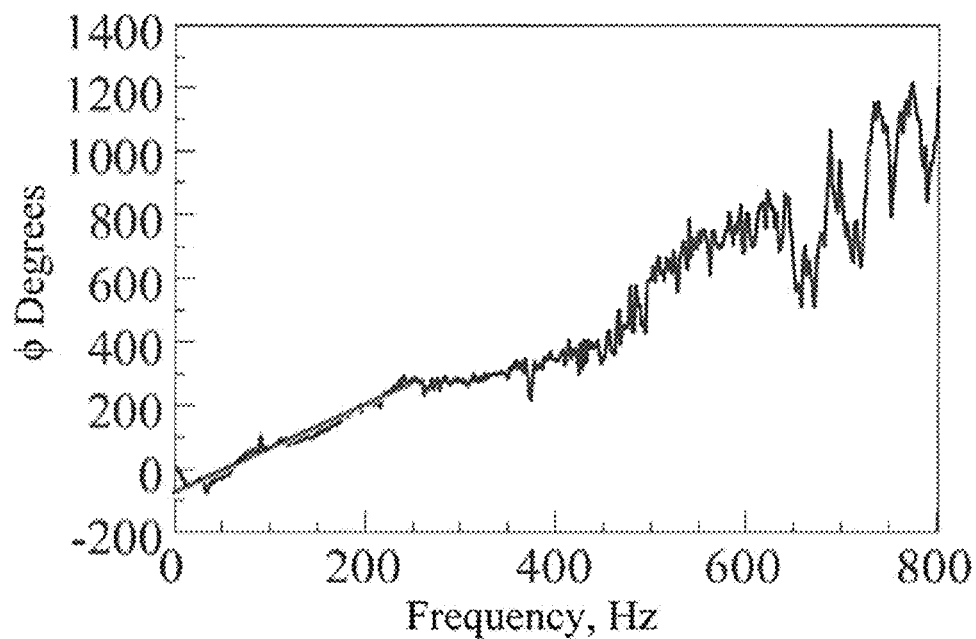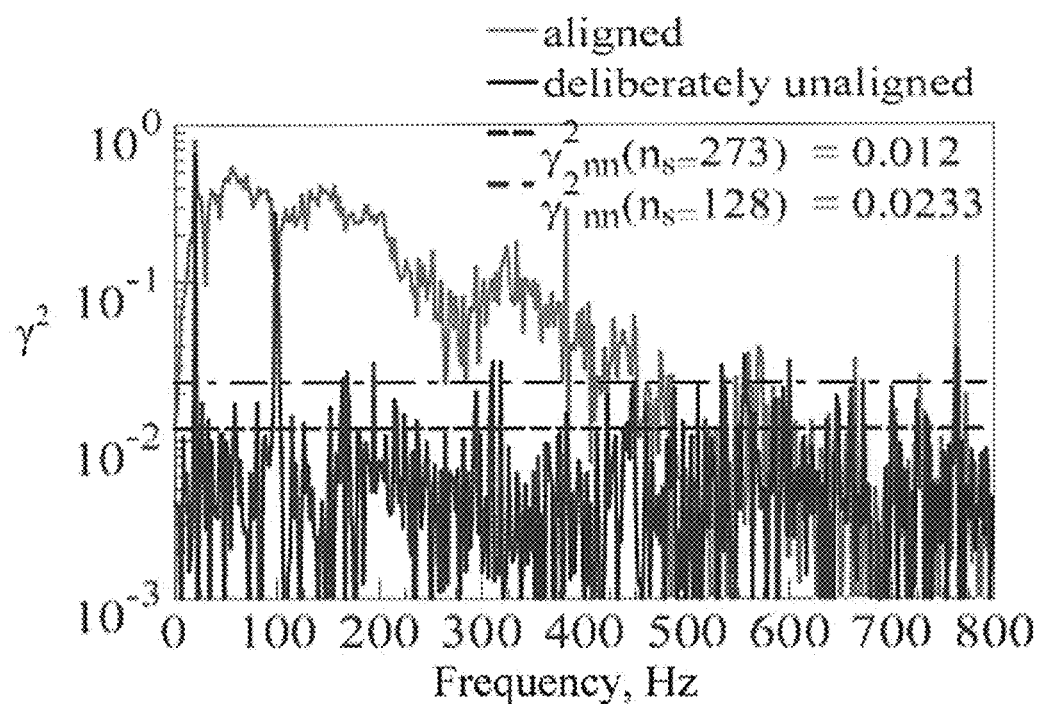

FIG. 7B – Cross-Spectrum Phase angle

FIG. 8A - Coherence

FIG. 8B – Cross-Spectrum Phase angle
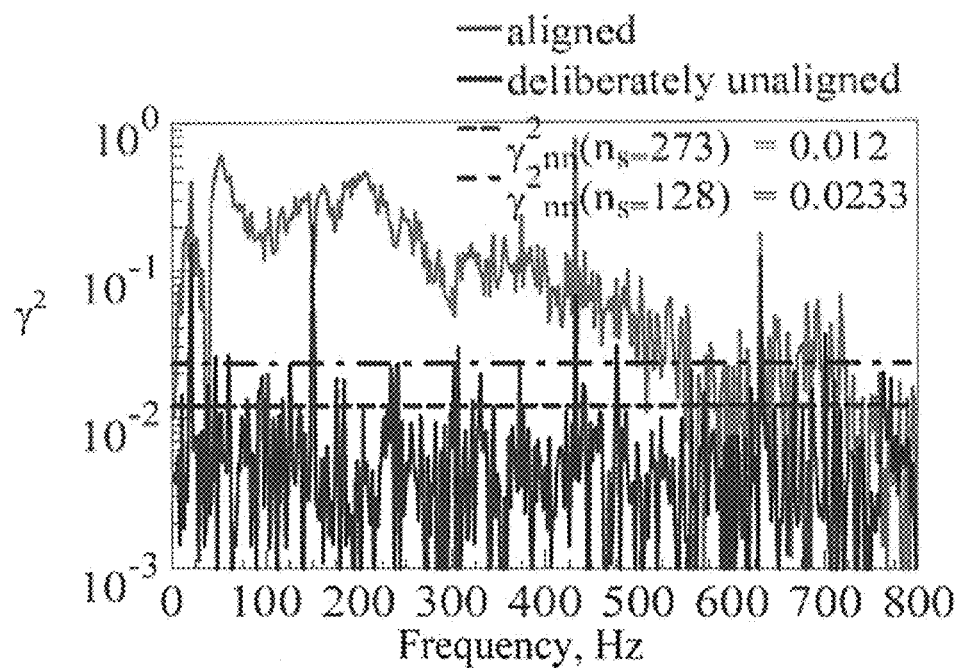
FIG. 9A - Coherence

FIG. 9B – Cross-Spectrum Phase angle

—aligned
—deliberately unaligned

$\gamma^2_{nn}(n_s=273) = 0.012$
$\gamma^2_{nn}(n_s=128) = 0.0233$
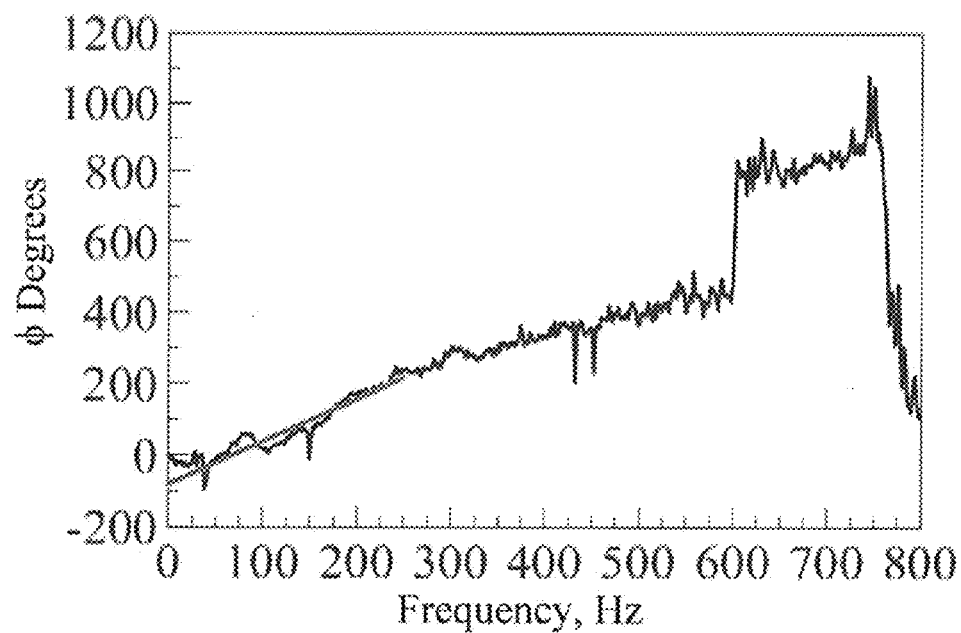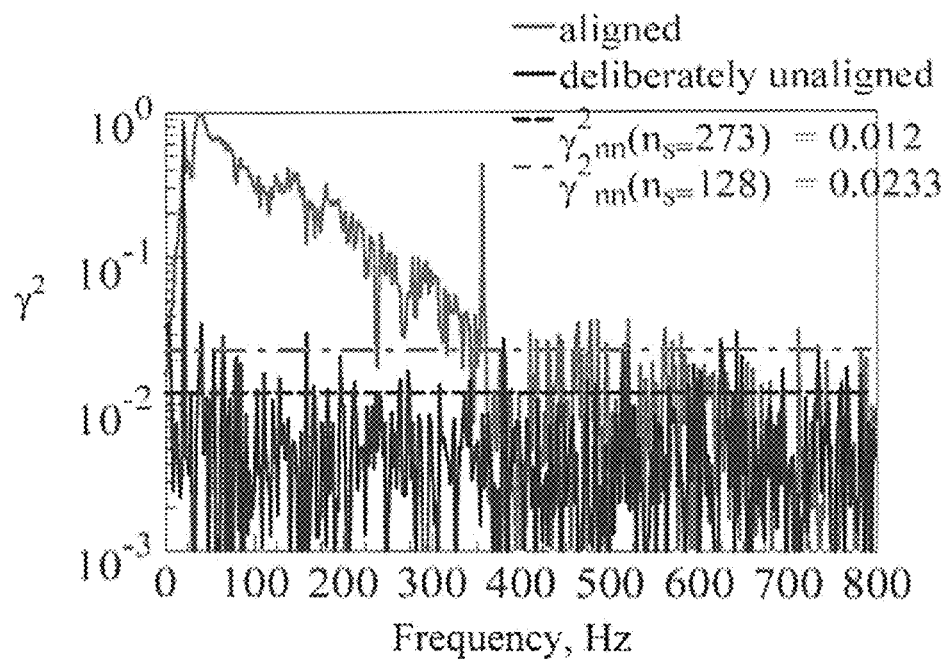
FIG. 10A - Coherence

FIG. 10B – Cross-Spectrum Phase angle

—aligned
—deliberately unaligned
$- \cdot -$ $\gamma^2_{nn}(n_s=273) = 0.012$
$- - -$ $\gamma^2_{nn}(n_s=128) = 0.0233$
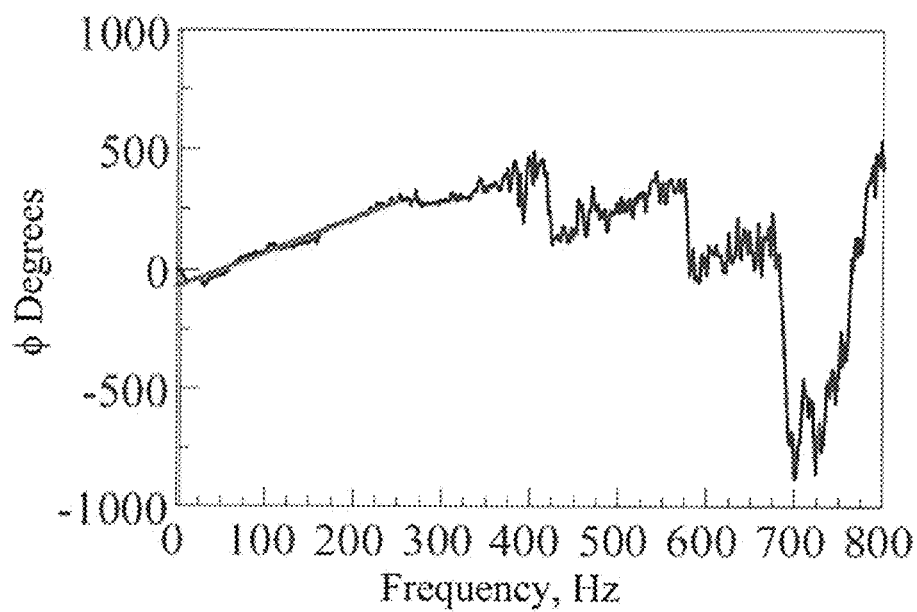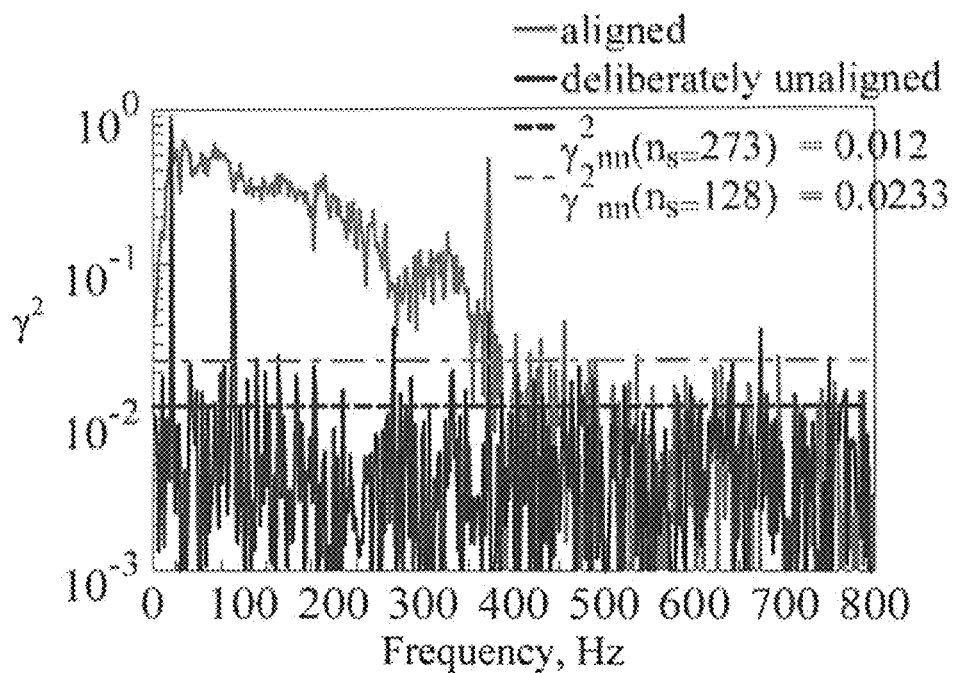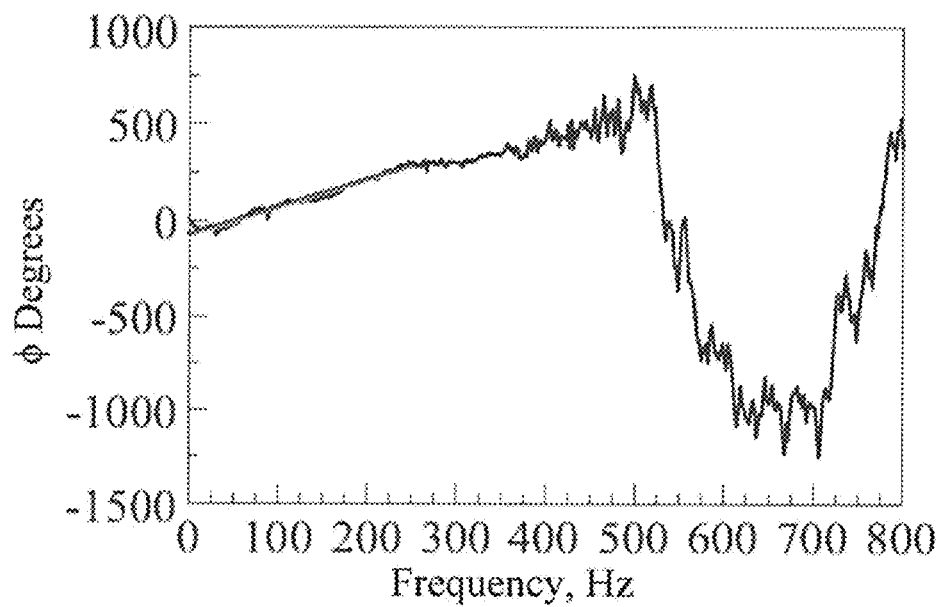
FIG. 11A - Coherence

FIG. 11B – Cross-Spectrum Phase angle
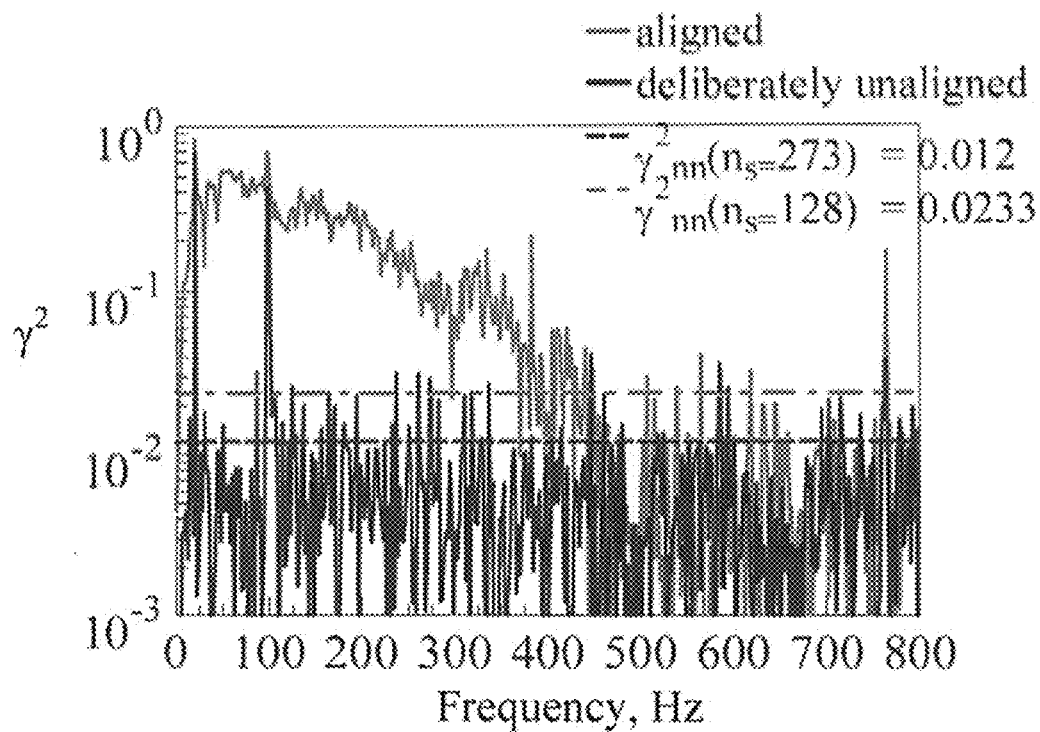
FIG. 12A - Coherence
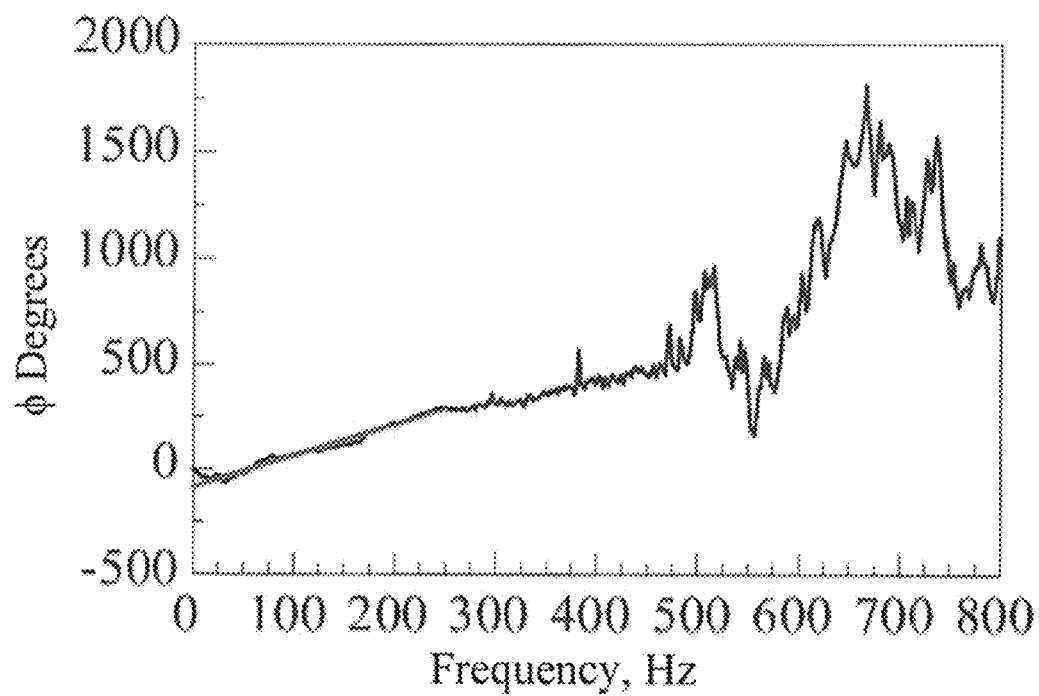
FIG. 12B – Cross-Spectrum Phase angle
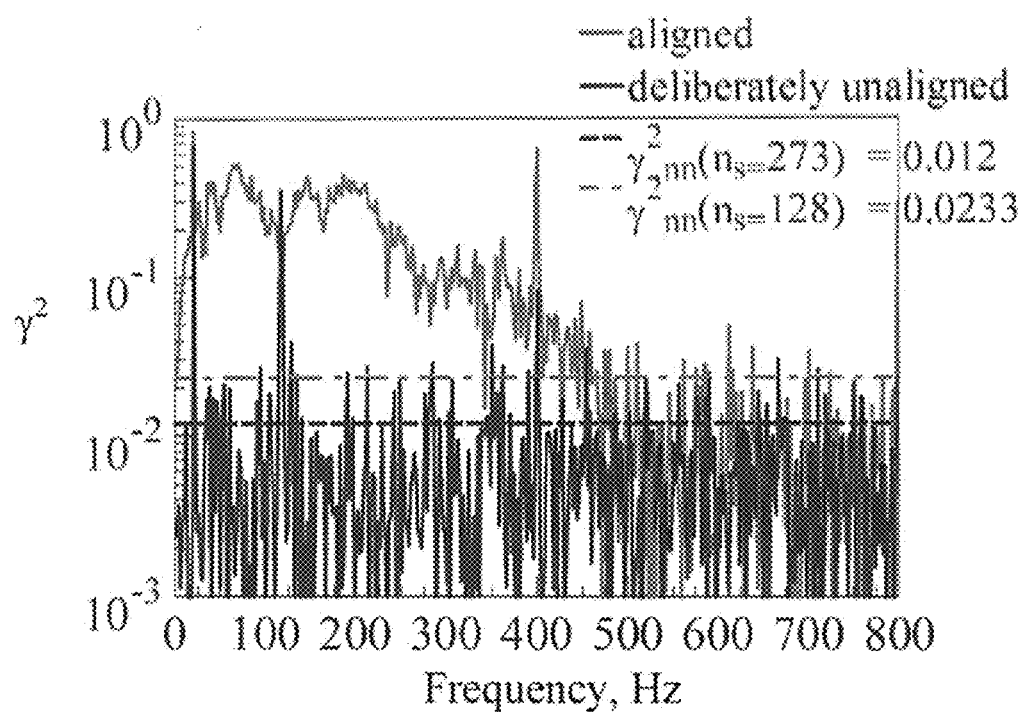
FIG. 13A - Coherence
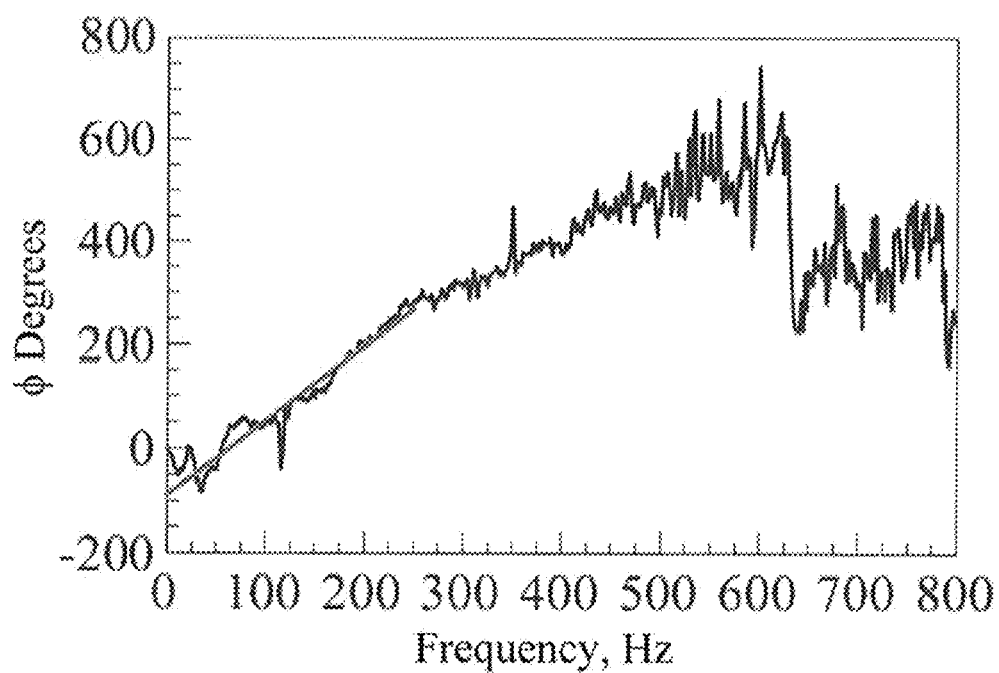
FIG. 13B – Cross-Spectrum Phase angle
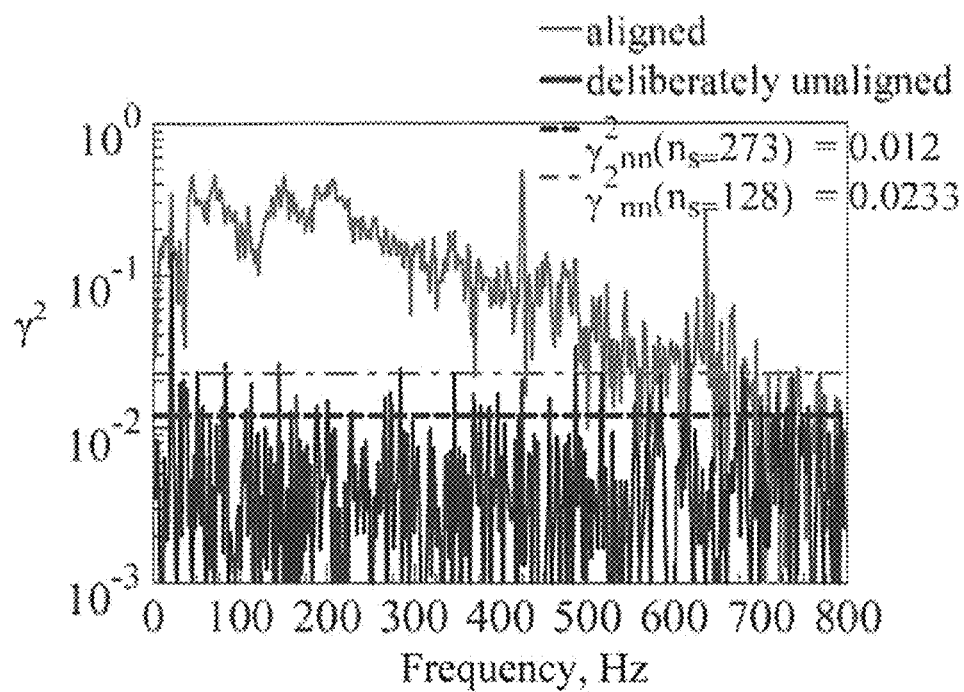
FIG. 14A - Coherence
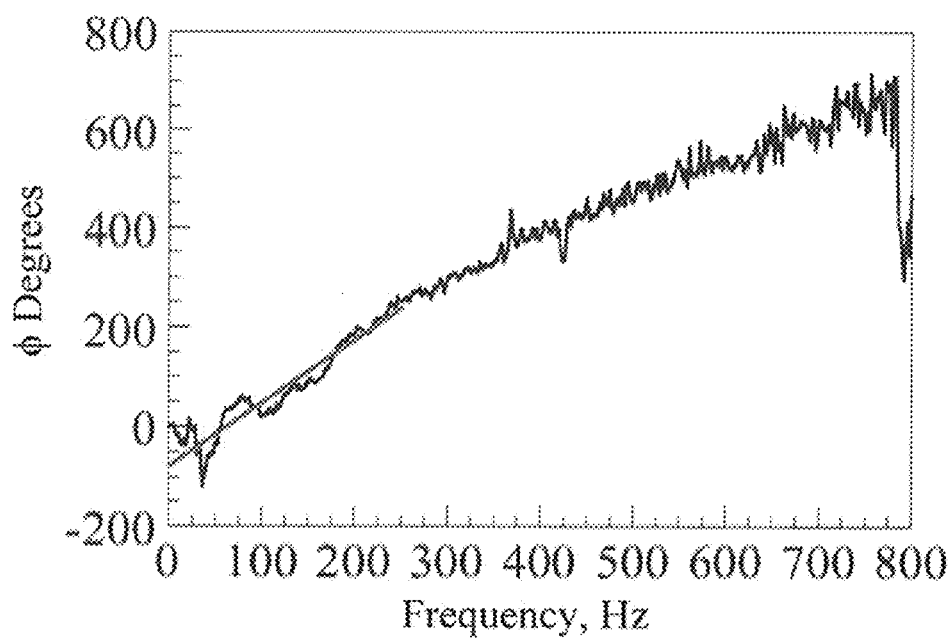
FIG. 14B – Cross-Spectrum Phase angle
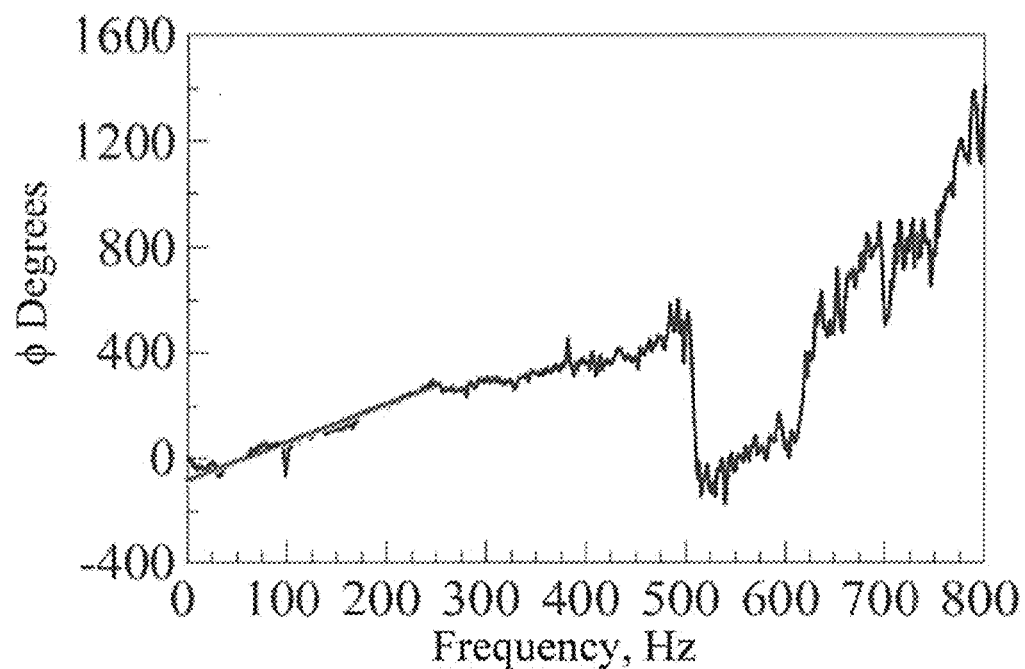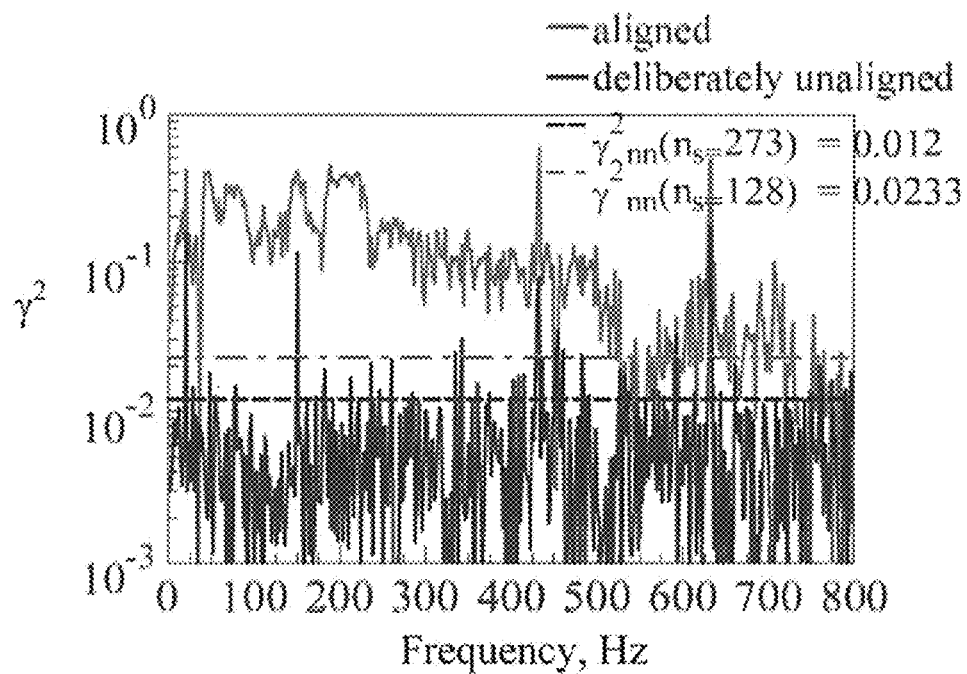
FIG. 15A - Coherence
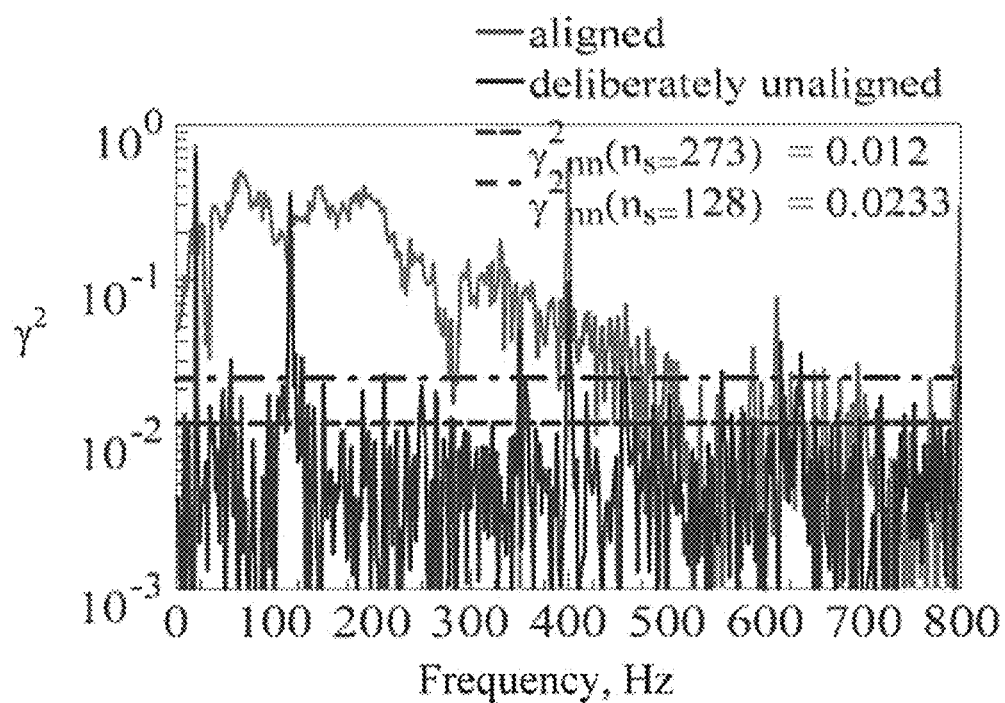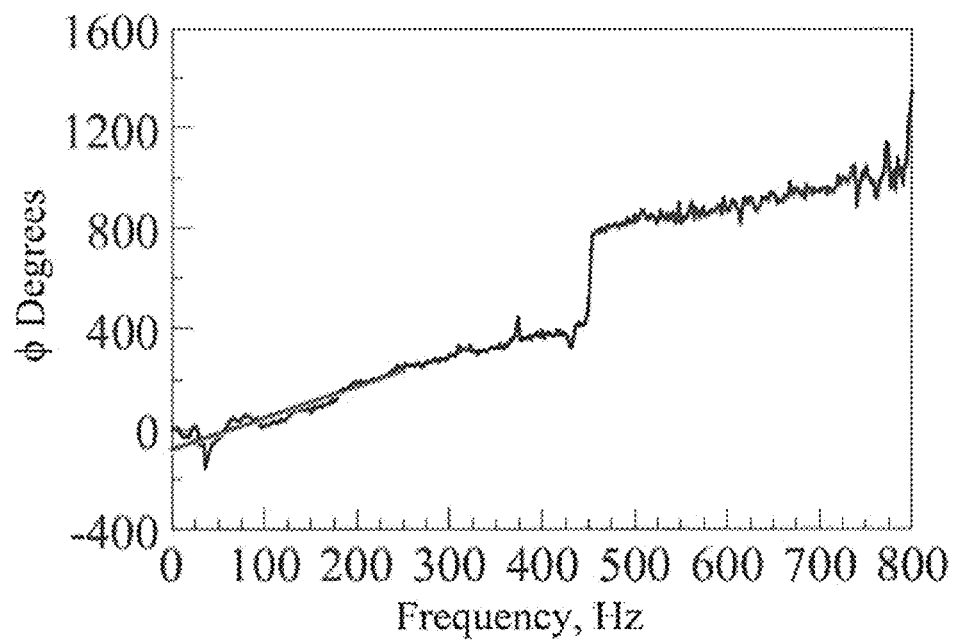

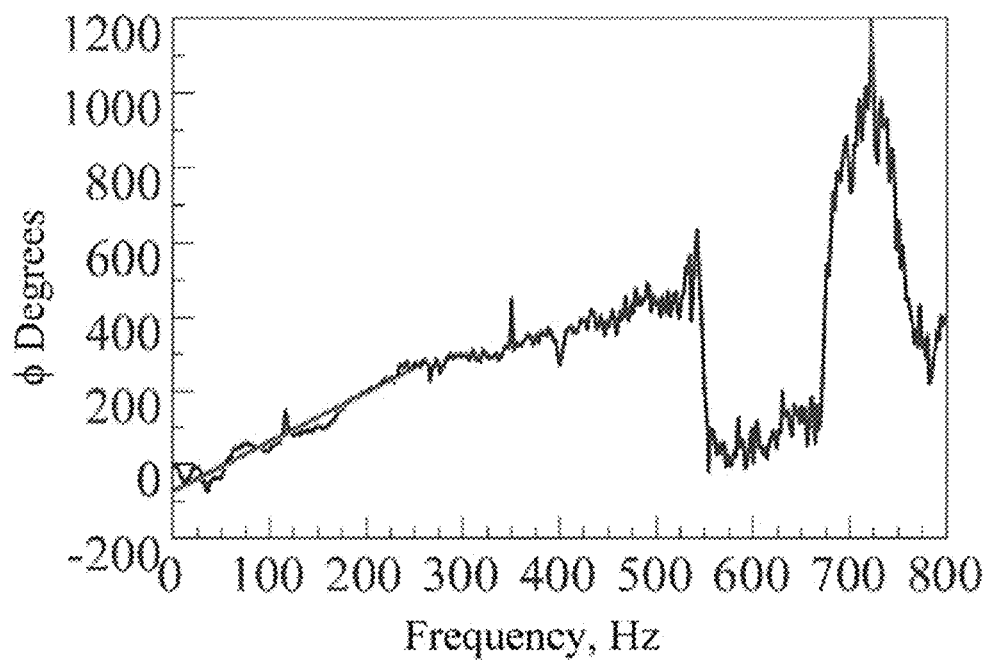FIG. 15B – Cross-Spectrum Phase angle

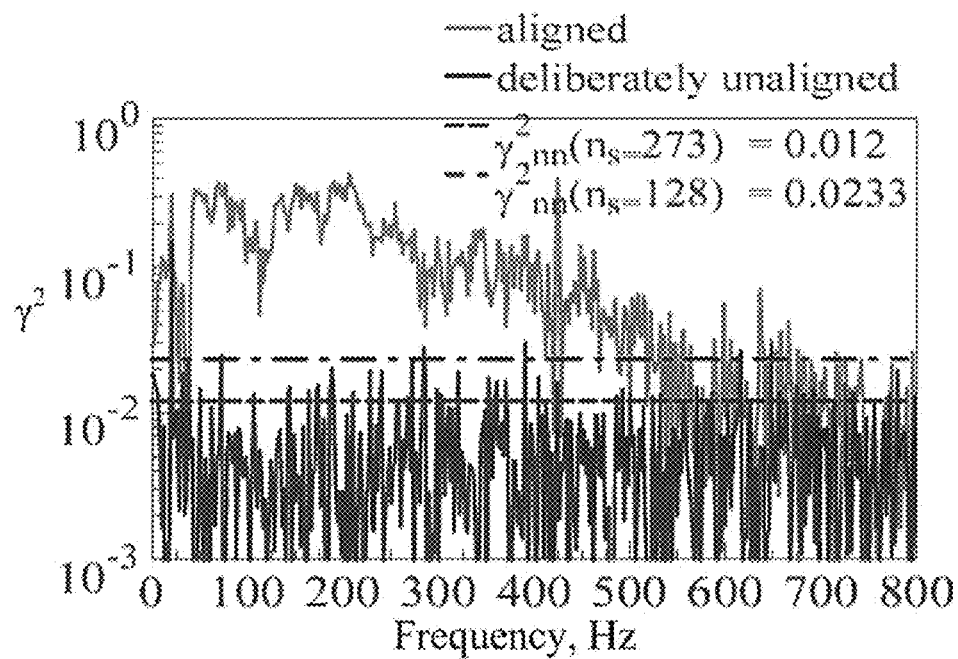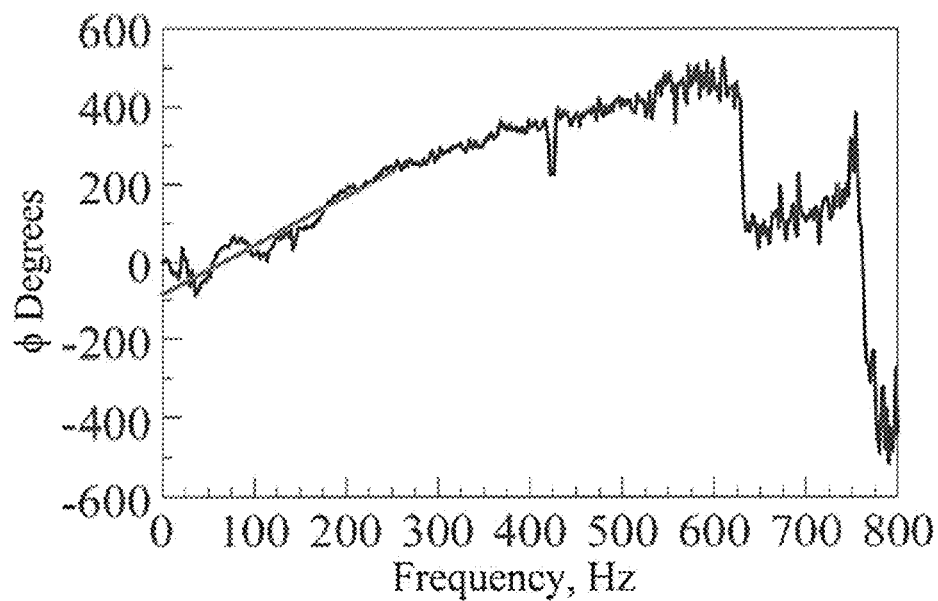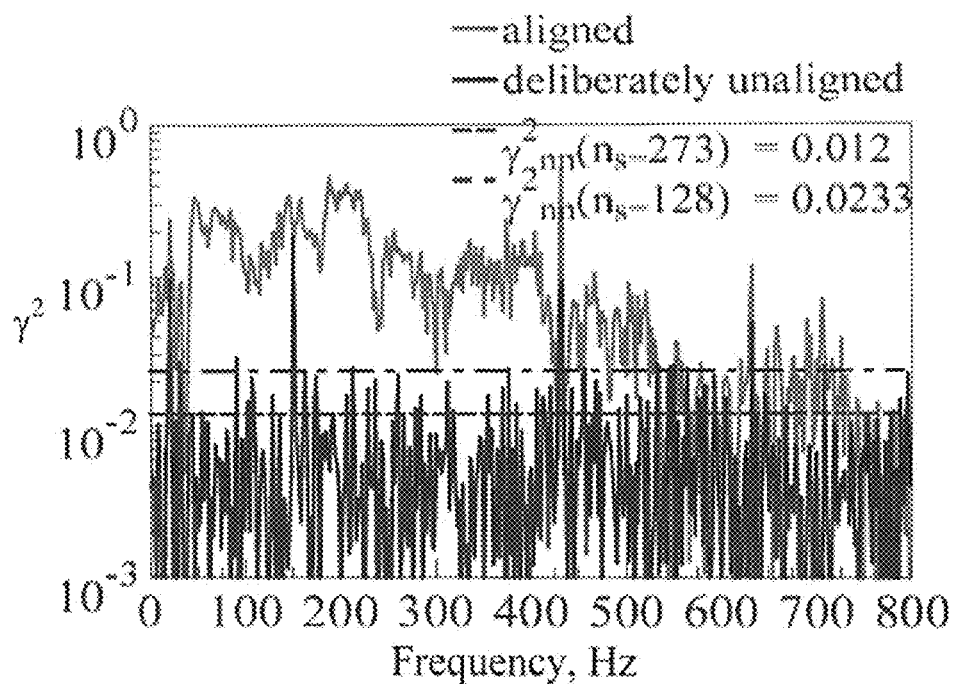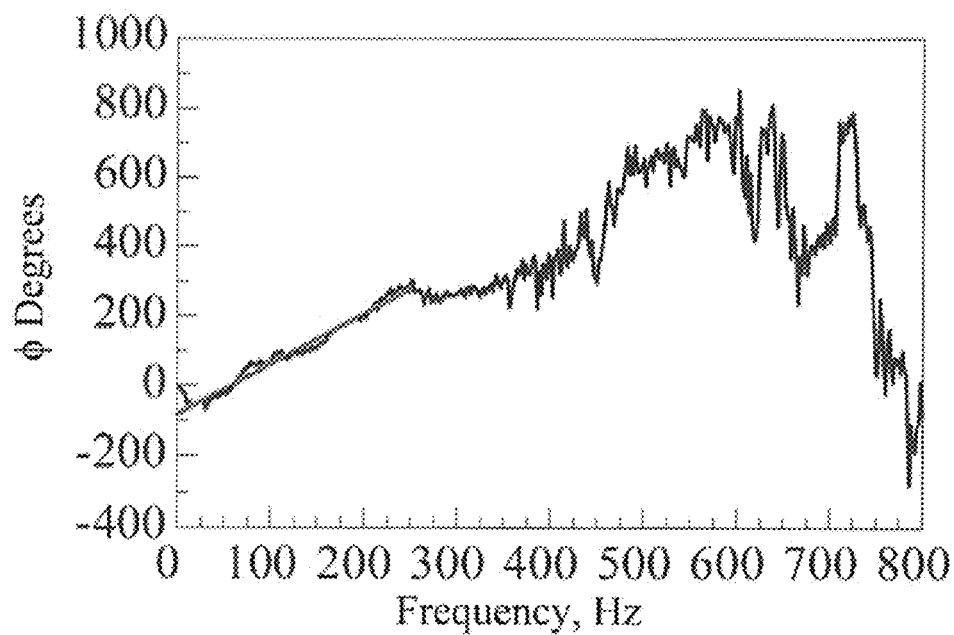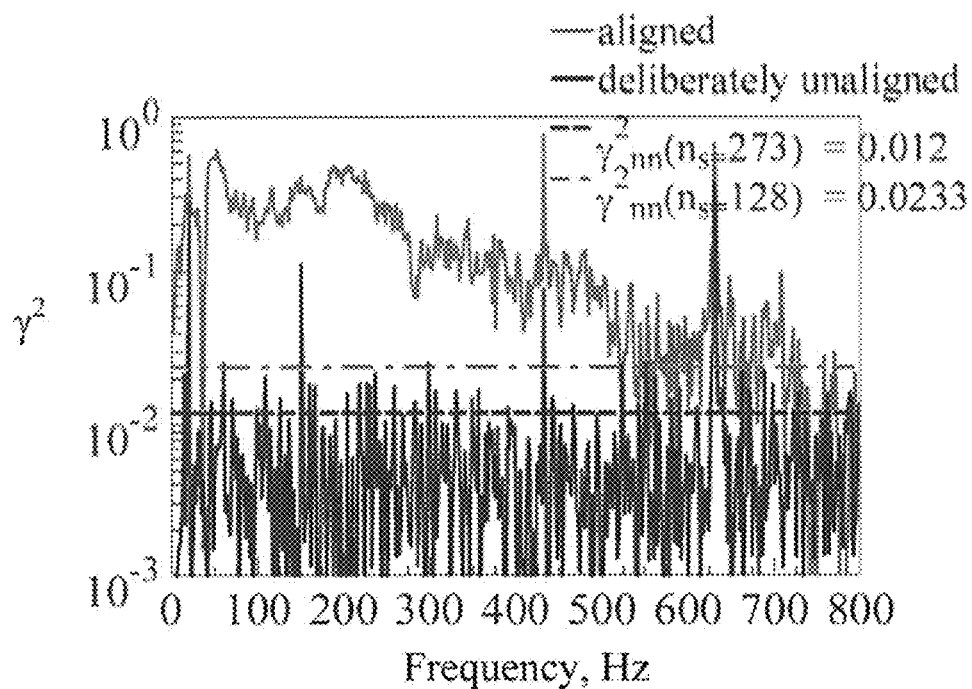FIG. 16A - Coherence

FIG. 16B – Cross-Spectrum Phase angle

FIG. 17

POST-COMBUSTION
RESIDENCE TIME
MEASUREMENT
SYSTEM   — 1800

                              — 1810
                    MEASUREMENT
                    COMPONENT

                              — 1820
SIGNALS FROM   RECEIVING/   POST-
PRESSURE   CALCULATION   COMBUSTION
SENSORS ON   COMPONENT   RESIDENCE TIME
ENGINE   OF ENGINE

                              — 1830
                    TABULATION
                    COMPONENT

                              — 1840
                    COMPUTATION
                    COMPONENT

FIG. 18

```
          ┌─────────────┐
          │    START    │
          └──────┬──────┘
                 │
                 ▼
      ┌──────────────────────┐
      │  PLACE PRESSURES     │
      │    SENSORS AT        │────  1902
      │  COMBUSTOR AND       │
      │   TURBINE EXIT       │
      └──────────┬───────────┘
                 │
                 ▼
      ┌──────────────────────┐
      │ MEASURE PRESSURES AT │
      │ COMBUSTOR ENTRANCE   │────  1904
      │  AND AT TURBINE EXIT │
      └──────────┬───────────┘
                 │
                 ▼
      ┌──────────────────────┐
      │  CALCULATE CROSS-     │
      │   SPECTRUM AND        │────  1906
      │ COHERENCE FUNCTIONS  │
      └──────────┬───────────┘
                 │
                 ▼
      ┌──────────────────────┐
      │  APPLY LINEAR CURVE  │
      │   FIT TO THE CROSS-   │
      │ SPECTRUM PHASE ANGLE │────  1908
      │ OVER AN APPROPRIATE  │
      │   FREQUENCY RANGE    │
      └──────────┬───────────┘
                 │
                 ▼
      ┌──────────────────────┐
      │  CALCULATE SLOPE OF  │
      │  THE LINEAR CURVE FIT│────  1910
      └──────────┬───────────┘
                 │
                 ▼
      ┌──────────────────────┐
      │  COMPUTE POST-       │
      │ COMBUSTION RESIDENCE │────  1912
      │  TIME FROM SLOPE OF  │
      │  LINEAR CURVE FIT    │
      └──────────┬───────────┘
                 │
                 ▼
          ┌─────────────┐
          │    STOP     │
          └─────────────┘
```

FIG. 19

FIG. 20

METHOD FOR MAKING MEASUREMENTS OF THE POST-COMBUSTION RESIDENCE TIME IN A GAS TURBINE ENGINE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent application Ser. No. 61/503,855 entitled "METHOD FOR MAKING MEASUREMENTS OF THE POST-COM-BUSTION RESIDENCE TIME IN A GAS TURBINE ENGINE" filed on Jul. 1, 2011. The entirety of the above-noted application is incorporated by reference herein.

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be manufactured and used only by or for the Government for Government purposes without the payment of any royalties thereon or therefore.

BACKGROUND

A challenging issue confronting the air transport system is the demand for the reduction of the emissions of oxides of nitrogen. The formation of thermal NO_x in a gas turbine engine depends on the stoichiometry, the residence time linearly, and on the reaction temperature exponentially. Zeldovich thermal NO_x may be produced by oxidation of atmospheric nitrogen in post flame gases. As turbine blade resistance to high temperatures improves, nitrogen production in the post-combustion zone may become more important. While residence time is not as significant as temperature in formula predicting NO_x production, it is a necessary factor and should be as accurate as possible. The characteristic combustor residence time can be defined as the ratio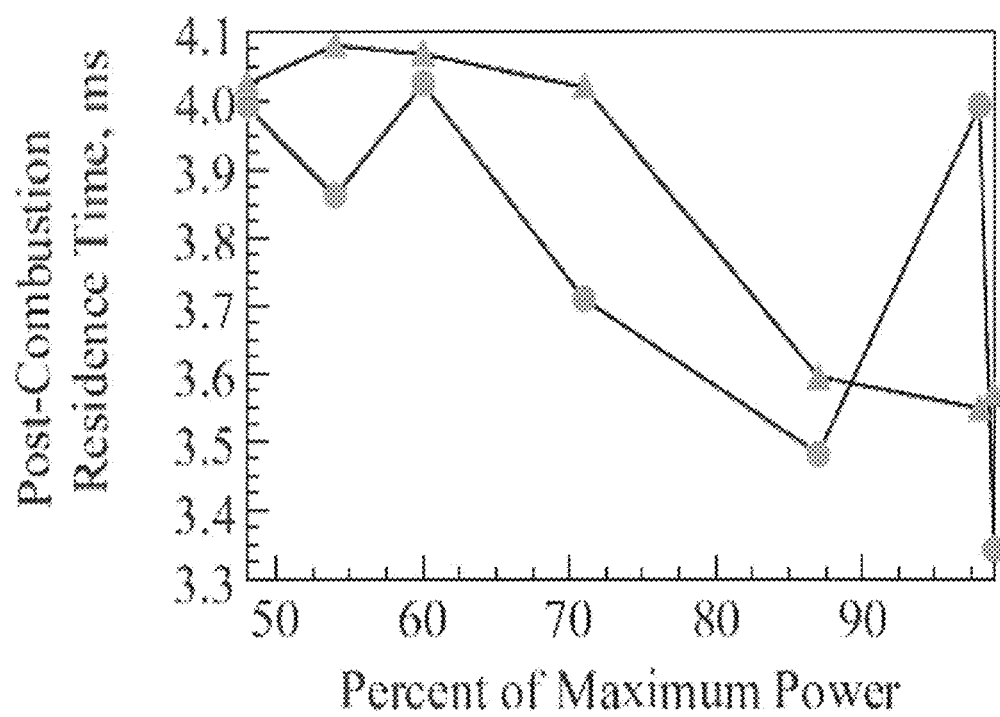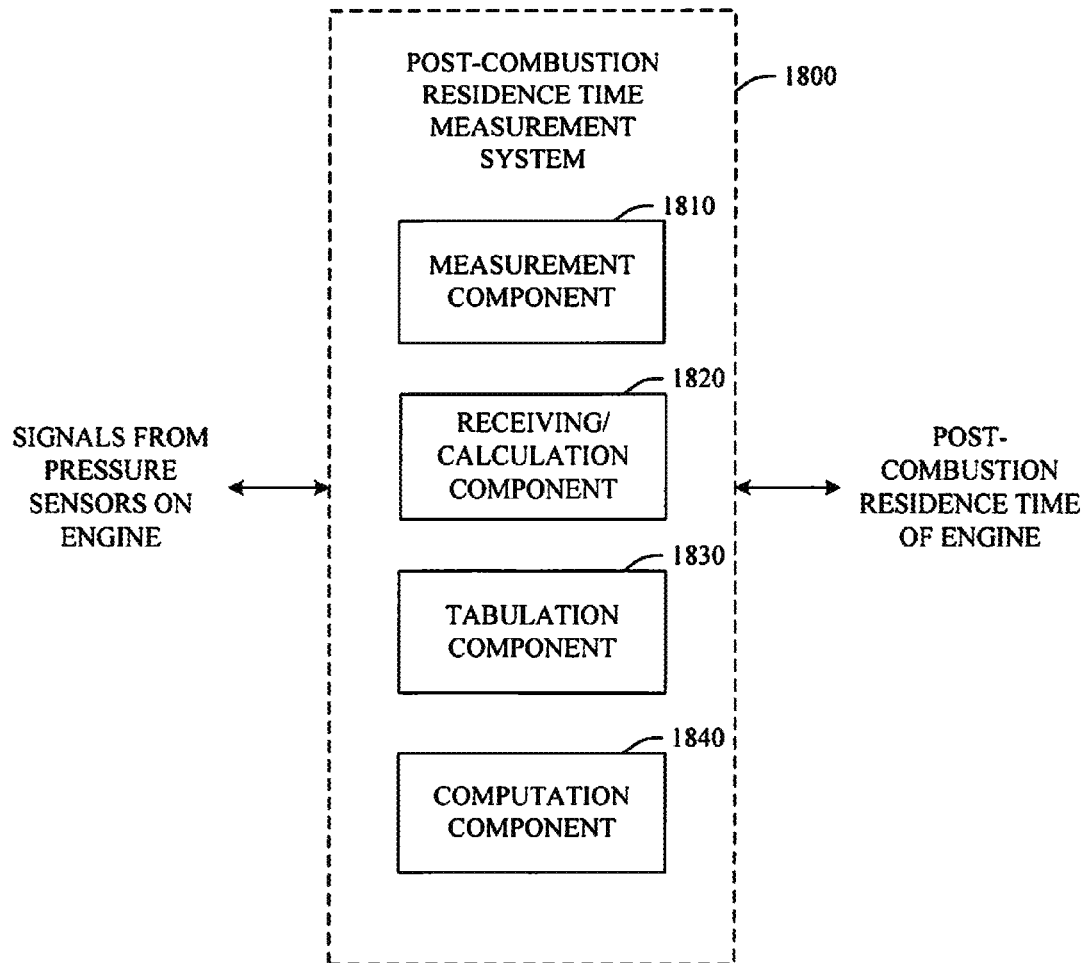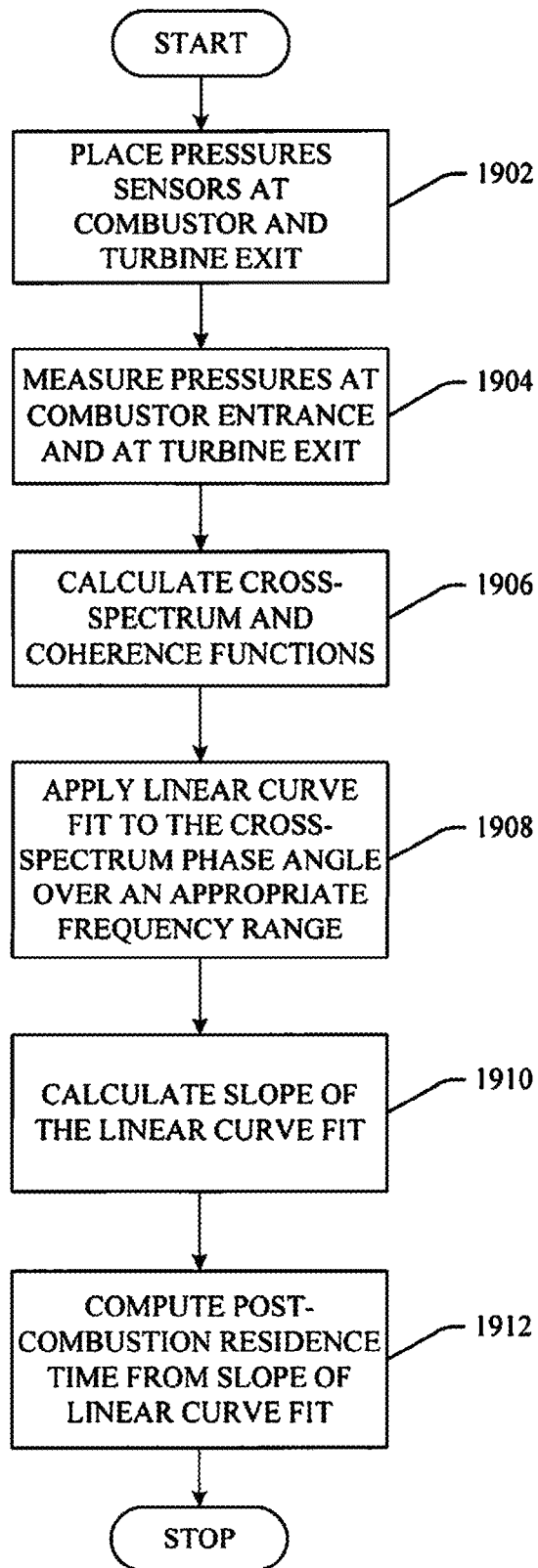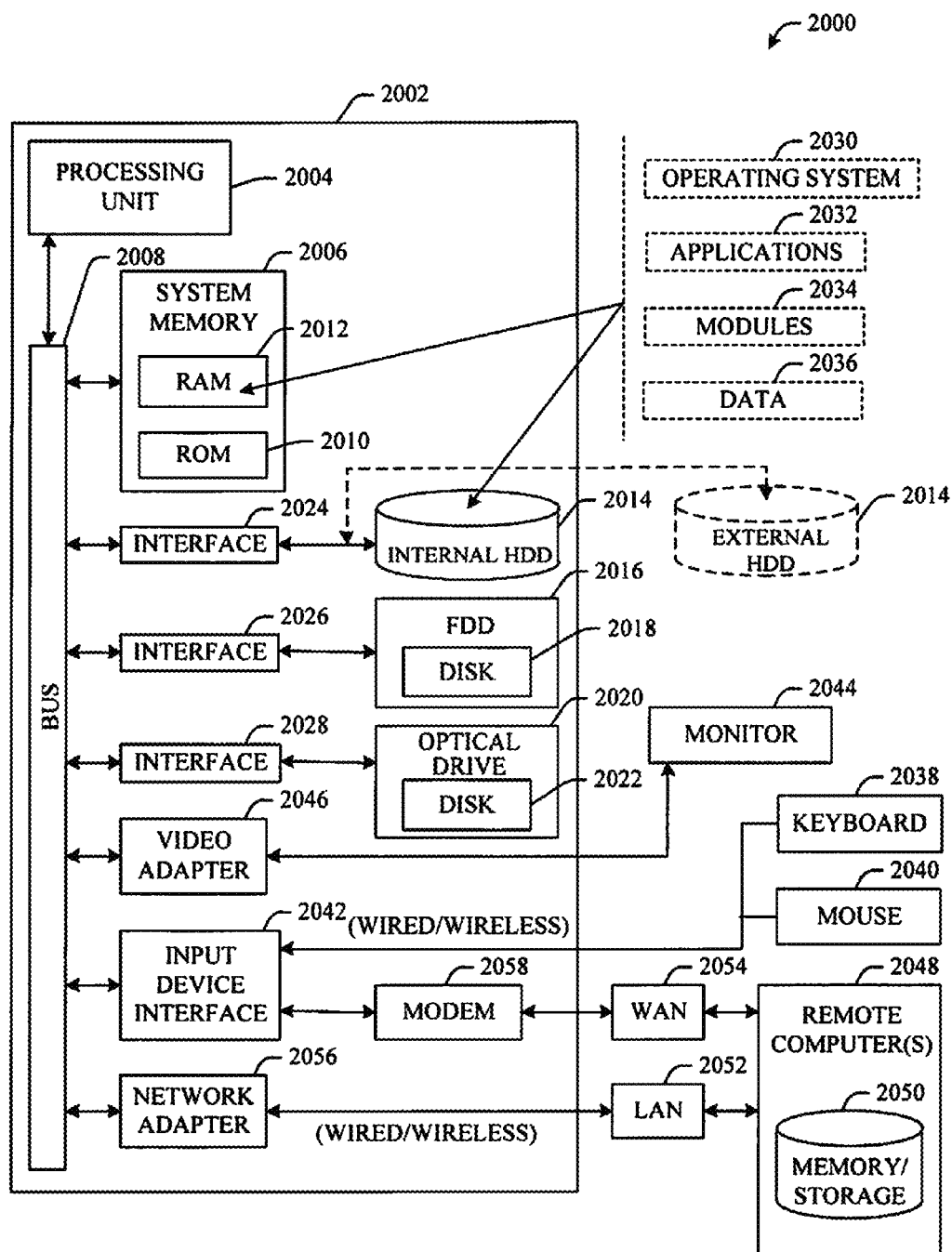 of the combustor volume to the bulk (volumetric) flow rate. This value is estimated from geometry and operational data. Detailed geometrical and operational data from gas turbine engine manufacturers, however, is frequently unavailable. Furthermore, post-combustion residence time measurements are not available to verify analytical estimates. Consequently, in order to improve the technology to satisfy future emission prediction goals, a different concept for determining the characteristic post-combustor residence time is required.

SUMMARY

The following presents a simplified summary in order to provide a basic understanding of some aspects of the innovation. This summary is not an extensive overview of the innovation. It is not intended to identify key/critical elements or to delineate the scope of the innovation. Its sole purpose is to present some concepts of the innovation in a simplified form as a prelude to the more detailed description that is presented later.

In an aspect of the innovation a different concept for determining characteristics of post-combustor residence time is disclosed. The concept is based on determining the post-combustion residence time delay due to convection of entropy at the flow speed in the combustor of a gas turbine engine over a range of operating conditions. It is evaluated from the slope of the combustor sensor signal/turbine exit signal pressure cross-spectrum phase angle over an appropriate frequency range where the measured signal can be attributed to indirect combustion noise.

In another aspect of the innovation the innovation, a method of measuring a residence time in a gas-turbine engine is provided, whereby the method includes placing pressure sensors at a combustor entrance and at a turbine exit of the gas-turbine engine and measuring a combustor pressure at the combustor entrance and a turbine exit pressure at the turbine exit. The method further includes computing cross-spectrum functions between a combustor pressure sensor signal from the measured combustor pressure and a turbine exit pressure sensor signal from the measured turbine exit pressure, applying a linear curve fit to the cross-spectrum functions, and computing a post-combustion residence time from the linear curve fit.

In yet another aspect of the innovation the innovation, a system to measure a post-combustion residence time in a gas-turbine engine is provided and includes a measurement component that measures a plurality of combustion and/or turbine flow pressures in the engine, a receiving/calculation component that calculates a plurality of cross-spectrum functions based on the measured plurality of combustion and/or turbine flow pressures, a tabulation component that tabulates a linear curve fit based on the calculated plurality of the cross-spectrum functions, and a computation component that computes the post-combustion residence time in the gas-turbine engine.

To accomplish the foregoing and related ends, certain illustrative aspects of the innovation are described herein in connection with the following description and the annexed drawings. These aspects are indicative, however, of but a few of the various ways in which the principles of the innovation can be employed and the subject innovation is intended to include all such aspects and their equivalents. Other advantages and novel features of the innovation will become apparent from the following detailed description of the innovation when considered in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of an example gas-turbine engine with instrumentation that can be utilized to measure post-combustion residence time in accordance with an aspect of the innovation.

FIG. 2 is a schematic illustration of a turbine-combustor-tailpipe noise system diagram in accordance with an aspect of the innovation.

FIGS. 3-9 are graphical illustrations of a magnitude squared aligned coherence (MSC) function in part (a) and a cross-spectrum phase angle in part (b) in accordance with an aspect of the innovation.

FIGS. 10-16 are graphical illustrations of a magnitude squared aligned coherence (MSC) function in part (a) and a cross-spectrum phase angle in part (b) in accordance with an aspect of the innovation.

FIG. 17 is a graphical illustration of post-combustion residence times as a function of engine power in accordance with an aspect of the innovation.

FIG. 18 illustrates an example system incorporating a method of measuring post-combustion residence time in a gas-turbine engine in accordance with an aspect of the innovation.

FIG. 19 illustrates an example flow chart of a procedure that measures post-combustion residence time in a gas-turbine engine in accordance with an aspect of the innovation.

FIG. 20 illustrates a block diagram of a computer operable to execute the disclosed architecture.

DETAILED DESCRIPTION

The innovation is now described with reference to the drawings, wherein like reference numerals are used to refer to

like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the subject innovation. It may be evident, however, that the innovation can be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to facilitate describing the innovation.

While specific characteristics are described herein (e.g., thickness), it is to be understood that the features, functions and benefits of the innovation can employ characteristics that vary from those described herein. These alternatives are to be included within the scope of the innovation and claims appended hereto.

While, for purposes of simplicity of explanation, the one or more methodologies shown herein, e.g., in the form of a flow chart, are shown and described as a series of acts, it is to be understood and appreciated that the subject innovation is not limited by the order of acts, as some acts may, in accordance with the innovation, occur in a different order and/or concurrently with other acts from that shown and described herein. For example, those skilled in the art will understand and appreciate that a methodology could alternatively be represented as a series of interrelated states or events, such as in a state diagram. Moreover, not all illustrated acts may be required to implement a methodology in accordance with the innovation.

Reducing NO_x emissions and aircraft fuel burn by more than 75% while achieving perceived cumulative noise levels 71 dB below stage 4 limits in subsonic vehicles is a future goal of the aerospace industry. Over the years studies have been conducted on gas turbine (turbofan) engines to evaluate turbine tone generation, attenuation of direct combustion noise, etc. Indirect combustion noise, on the other hand, was initially thought to be a non-contributor to the engine core noise and, thus, was investigated only analytically and in model scale tests.

Low frequency noise generated in the turbofan engine core may make a significant contribution to the overall noise signature in the aft direction at the low power settings, which are used on an airport flight approach trajectory. This type of low frequency noise may be a problem for future aircraft. Two possible low frequency noise sources are "direct" and "indirect" combustion noise. The source of combustion noise attributed to the unsteady pressures produced by the unsteady combustion process that propagate through the turbine to the far field is called the "direct" combustion noise source. The other source of turbofan engine combustion noise is known as the "indirect" mechanism in which the noise is generated in the turbine by the interaction of entropy fluctuations, which also originate from the unsteady combustion process, as they propagate through regions characterized by mean flow velocity or pressure gradients in the turbine stages. The innovation disclosed herein uses measured data from the indirect combustion noise in the combustor and the turbine exit to directly measure the post-combustion residence time.

The formation of thermal NO_x depends on the stoichiometry, the residence time linearly, and on the reaction temperature exponentially. Zeldovich thermal NO_x may be produced by oxidation of atmospheric nitrogen in the post flame gases. As turbine blade resistance to high temperatures improves, nitrogen production in the post-combustion zone may become more important. NO_x levels increase with increasing post-combustion residence time. The characteristic combustor residence time can be defined as the ratio of the combustor volume to the bulk (volumetric) flow rate. This information, however, is proprietary, which limits the information avail-

able about the post combustion residence time in current and future combustor design concepts. Thus, the innovation discloses an alternate concept for determining the characteristic post-combustor residence time. The innovation determines the post-combustion residence time delay due to convection of entropy at the flow speed in the combustor. It is evaluated from the slope of the combustor sensor signal/turbine exit signal pressure cross-spectrum phase angle over an appropriate frequency range where the measured signal can be attributed to indirect combustion noise.

The net travel time of the indirect combustion noise signal from the combustor to the turbine exit and the far field increases since the travel velocity of the entropy fluctuations to the turbine is the flow velocity, which is a small fraction of the speed of sound, in the combustor. The innovation demonstrates that the pressure and entropy should be in phase in the combustor. As a result, the pressure signal from an indirect combustion noise source would be delayed relative to a pressure signal from a direct combustion noise source since an indirect combustion noise signal does not travel with the speed of an acoustic wave until it interacts with the turbine.

The innovation shows that the cross-spectra and correlation function between a combustor sensor and far-field microphones are tools that provide a way to separate "direct" and "indirect" coherent combustion noise due to this travel delay time. This paper uses measurements in the combustor and turbine exit from a test engine to directly measure the post-combustion residence time. The innovation uses tools that are part of signal-processing theory to study a combustor pressure sensor signal and a turbine exit pressure sensor signal. The cross-spectral density phase measurement identifies a time delay that corresponds to the convective time delay. The magnitude of the coherence between the two sensors identifies the spectral region of importance as being in the 50-250 Hz frequency range. The innovation discloses the cross-spectral density phase angle and the coherence over a range of operating conditions and calculates the post-combustion residence time from the slope of the cross-spectral density phase angle.

Prior to disclosing the innovation, the information disclosed herein will be presented as follow: 1) First expressions for NO_x emission; 2) First expressions for residence time; 3) Engine noise data; 4) A linear system theory; 5) A system model; 6) Results; and 7) The post-combustion residence time results calculated from the cross-spectrum between a combustor pressure sensor and a turbine exit pressure sensor are presented.

The operation of a gas turbine engine can be correlated with NO_x emission levels using regression analysis of measurable test parameters or by consideration of time scales and chemical kinetics or using both sets of variables along with such variables as equivalence ratio, fuel flow rate and Mach number. A correlation of NO_x emission levels determined by others for propane air combustion is based only on the residence time and adiabatic flame temperature. It was determined that the NO levels are principally a function of adiabatic flame temperature and combustor residence time, which is represented by the expression:

$$E_{NO_x} = t_{res}\exp\left\{-72.28 + 2.80\sqrt{T_{adiabatic}} - \frac{T_{adiabatia}}{38.02}\right\} \tag{1}$$

where E_{NO_x} is the NO_x emission index (gNO$_2$/kg–fuel), $T_{adiabatic}$ is the adiabatic flame temperature (° K), and t_{res} is the combustor residence time (ms). They found that over the

5

6

range of pressures from 5 to 30 atmospheres, there is no significant observed departure from this expression for inlet temperatures 727K and higher.

Combustor residence time $\tau_{residence}$ is given by the bulk flow through the combustor volume expressed in equation (2):

$$\tau_{residence} = \frac{volume}{volumetricflowrate} = \frac{VP}{mRT} \qquad (2)$$

Others have stated that that the residence time in a conventional combustor and in a micro-combustor is approximately 7 ms and 0.5 ms respectively.

The primary combustion zone residence time can also be calculated by equation (3):

$$\tau_{PZ} = \frac{V_{PZ}\rho_{combair}}{\dot{m}_{PZ}} \frac{T_{inlet}}{T_{AD,PZ}} \qquad (3)$$

In examining a set of exemplified gas turbine dual fuel, dry low emission combustion system, primary zone residence times were found to be 2.71, 1.35, 8.17, 4.09, 9.84, and 4.92 ms.

Gas turbine NO_x production, however, is more complicated than NO_x emission from a propane combustor, described above, since in addition to the resident time dependence the reaction rate is assumed to be a function of pressure in addition to temperature or:

$$\text{reaction rate}=p^m\exp(zT) \qquad (4)$$

and the mixing rates are assumed to be a function of linear pressure drop or:

$$\text{mixing rate}=(\Delta P/P)x \qquad (5)$$

Consequently,

$$E_{NO_x} = A\left(\frac{PV}{\dot{m}_A T}\right)\left(\frac{\Delta P}{P}\right)^x P^m\exp(zT) \qquad (6)$$

$$= \frac{AV_c(\Delta P)^x P^{(l+m-x)}\exp(zT)}{\dot{m}_A T}$$

Others have correlated a large set of engine data using A=9× 10^{-8}, x=0, m=0.25, and z=0.01 so that:

$$E_{NO_x} = \frac{9.0\times10^{-8}V_cP_3^{1.25}\exp(0.01T_{st})}{\dot{m}_A T_{pz}} \qquad (7)$$

Still others recast equation (7), thereby making changes to improve correlation with data and derived:

$$E_{NO_x} = \frac{1.5\times10^{15}(\tau_{NO_x} - 0.5\tau_{ev})^{0.5}\exp(-71100/T_{St})}{P_3^{0.06}(\Delta P_3/P_3)^{0.5}} \qquad (8)$$

where τ_{NOx} is the residence time in the NOx production region, τ_{ev} is the evaporation time, T_{st} is the reaction temperature, P_3 is the combustor inlet pressure, and $(\Delta P_3/P_3)$ is the combustor pressure drop.

Consequently, the primary zone residence time has evolved to become a NO_x emission production parameter evaluated by doing a least squared curve fit to a large data set. The primary zone residence time formulation has become more complex as combustor design has become more complex. In part, this may be due to it not being a measurable quantity. When used as correlation factor it should be referred to as a primary zone NO_x emission residence time and not as the primary zone residence time. As mentioned above, the innovation disclosed herein uses a procedure to measure the post-combustion residence time using signal processing methods. As a consequence, this post-combustion/post-flame residence time becomes available for consideration with knowledge of any engine company proprietary combustor geometry design information or proprietary operating parameters.

Referring now to the figures, FIG. 1 is an example engine 100 that can be utilized to conduct experiments to obtain engine test data and FIG. 2 illustrates a turbine-combustor-tailpipe noise system diagram 200 in accordance with an aspect of the innovation. The engine 100 is a dual-spool, turbofan engine that has a direct drive, a wide chord fan connected by a long shaft to a low-pressure turbine spool and a high-pressure compressor connected by a concentric short shaft to a turbine high-pressure spool. The fan diameter is approximately 34.2 in. The combustor design is a straight-through-flow annular geometry with 16 fuel nozzles and 2 igniters.

The engine-internal instrumentation in this configuration includes a high-temperature pressure sensor with air cooling in a combustor igniter port 102 (hereinafter "combustor sensor"), a first 104 high-temperature pressure sensor with air cooling at a first turbine exit (hereinafter "first turbine exit sensor") and a second 106 high-temperature pressure sensor with air cooling at a second turbine exit (hereinafter "second turbine exit sensor").

The data acquisition system had a sampling rate of 65 536 Hz and a sampling duration of approximately 70 s. The spectra were calculated using a 50 percent overlap, which permitted data reduction using approximately 254 overlapped ensemble averages at a bandwidth resolution of 2 Hz. Signal estimation parameters are shown in Table 1 below.

TABLE 1

Spectral estimate parameters.	
Parameter	Value
Segment length, (data points per segment), N	32 768
Sample rate, r_s, samples/s	65 536
Segment length, $T_d = N/r_s$, s	0.500
Sampling interval, $\Delta t = 1/r_s$, s	1/65 536
Bandwidth resolution, $B_e = \Delta f = 1/T_d = r_s/N$, Hz	2.0
Upper frequency limit, $f_c = 1/2\Delta t = r_s/2$, Hz	32 768
Propagation time delay/lag (T = 9° C., r = 30.43 m) $\tau_p = 5\,927/65\,536$, s	0.09044
Number of independent samples, n_s	128
Overlap	0.50
Sample length, T_{total}, s	≈70

The spectra and cross-spectra are estimated using a non-parametric method, which is based on averaging multiple windowed periodograms using overlapping time sequences. Using these spectra and cross spectra, the magnitude squared coherence is calculated to measure the similarity of the amplitude variations at particular frequencies. The ^ accent will be used to denote the statistical basis of a variable. This is done to avoid confusion with calculations of coherence using a single segment or block which yield a coherence of unity. The concept used is based on determining the post-combustion residence time delay due to convection of entropy at the flow

speed in the combustor. It is evaluated from the slope of the combustor sensor signal/turbine exit signal pressure cross-spectrum phase angle over an appropriate frequency range where the measured signal can be attributed to indirect combustion noise.

The appropriate frequency range is determined from the combustor sensor signal/turbine exit signal magnitude squared aligned coherence (MSC) function illustrated in equation (9) below.

$$\hat{\gamma}_{x,y}^2 = \frac{|\hat{G}_{x,y}|^2}{\hat{G}_{x,x}\hat{G}_{y,y}} \tag{9}$$

FIGS. **3-9** illustrate the MSC function in part (a) and the cross-spectrum phase angle in part (b) where the post-combustion residence time is at various percentages of maximum power as measured by the combustor sensor **102** and the first turbine exit sensor **104**. Specifically, FIGS. **3-9** are at 48, 54, 60, 71, 87, 98, and 99 percent of maximum power respectively.

Further, FIGS. **10-16** illustrate the MSC function in part (a) and the cross-spectrum phase angle in part (b) where the post-combustion residence time is at various percentages of maximum power as measured by the combustor sensor **102** and the second turbine exit sensor **106**. Specifically, FIGS. **10-16** are at 48, 54, 60, 71, 87, 98, and 99 percent of maximum power respectively.

Also illustrated in part (a) of FIGS. **3-16** is a coherence threshold calculated from:

$$\hat{\gamma}_{x_n x_n}^2(n_s) = 1 - (1-P)^{1/(n_s-1)} \tag{10}$$

where this formula determines a P-percent threshold confidence interval using the number of data segments/blocks, n_s, used in the periodogram method spectral estimator. The 95 percent confidence interval based on n=128 independent samples is 0.0233. The spectra are calculated using a 50 percent overlap and the 95 percent confidence interval based on n=273 samples is 0.0109. These indicators show the MSC function is reliable up to about 400 Hz. However, MSC function is above 0.1 only in a region from 30-250 Hz. The phase angle variation in this region is attributed to indirect combustion noise.

Instead of relying on the confidence interval given by Eq. (10), which is based on a statistical theory, to obtain a threshold value for $\hat{\gamma}_{nm}^2(n_s)$, a deliberately unaligned time history can be used to create the threshold value. If one of the time histories is shifted by a time delay more than the segment/block length, $Td=N/r_{s1}$, then the two time histories are totally independent unless tones are present. This deliberate de-correlation establishes a coherence threshold and also identifies any tones in the signals. Shifting the signals by this time delay removes the coherence of random noise but leaves the coherence of periodic functions which are sometimes identified as hidden periodicities, concealed spectral lines, or un-damped sinusoids in noise. The deliberately unaligned coherence is also shown in part (a) of FIGS. **3-9**. Note that the higher statistical confidence interval based on the number of independent records (n_d=128) is a more conservative estimate of the measured coherence threshold. The statistical coherence threshold can be used with confidence since it can be compared with a measured coherence threshold. The coherence value is below the 95 percent statistical confidence interval above 400 Hz. Consequently, this is the upper frequency limit for which data is available for analysis using a linear system model.

The methods used herein are based on system theory developed for linear systems with random inputs. The linear system theory disclosed herein is in the frequency domain. The output spectral density function, G and the cross-spectra density function, G, is related to an input spectral density function, G through frequency response function, H, representing the turbine as

$$\hat{G}_{y,y} = |H_{x,y}(f)|^2 \hat{G}_{x,x} \tag{11}$$

and

$$G_{x,y} = H_{x,y}(f)\hat{G}_{x,x}. \tag{12}$$

where x is the input signal from the high-temperature pressure sensor with air cooling in a combustor igniter port **102** and y is the output signal from either the first **104** or second **106** high-temperature pressure sensor with air cooling at the turbine exit.

The cross spectral density and the frequency response functions are complex valued quantities, which can be expressed in terms of a magnitude and an associated phase angle. This will be expressed herein using complex polar notation.

$$\hat{G}_{x,y}(f) = |\hat{G}_{x,y}(f)| \exp[j\hat{\phi}(f)] \tag{13}$$

$$H_{x,y}(f) = |H_{x,y}(f)| \cdot \exp[-j\psi(f)] \tag{14}$$

Before plotting the cross spectral density phase angle, phase unwrapping is applied to the phase angle to avoid a jump of 2π in the phase caused by the ATAN2 function.

The system under consideration has a combustion noise input with a measured spectrum, G, which includes acoustic and hydrodynamic components. The system measured output quantities are assumed to be related as follows:

$$\hat{G}_{9,10}{}^m(f) = H_{9,10}{}^m(f)\hat{G}_{9,9}{}^m(f) \tag{15}$$

$$\hat{G}_{10,10}{}^m(f) = |H_{9,10}{}^m(f)|^2 \hat{G}_{9,9}{}^m(f) \tag{16}$$

and the measured MSC by:

$$\hat{\gamma}_{9,10}^2 = \frac{|\hat{G}_{9,10}^m|^3}{\hat{G}_{9,9}^m \hat{G}_{10,10}^m} \tag{17}$$

where m indicates noise may be included in the measured quantities. The unknown that will be identified is the turbine frequency response function, $H^m(f)$ at a range of operating conditions.

The system model disclosed herein is applied in the 50-250 Hz frequency range. The model involves the turbine attenuation and the convective time delay of the of the entropy signal. The plant being modeled is the turbine. The input to the plant is the total pressure signal and the measurement made in the combustor is of the total pressure signal. Consequently, the available input auto-spectrum is that of the total pressure signal. To aid in physical interpretation, a standard template parametric model form will be used. The model form disclosed herein is in a parametric reduced order frequency domain representation. The parameters depend nonlinearly on the operating point. However, at each operating condition the system will be assumed to be linear and the same parametric form will be used so that source separation will be obvious. The nonlinear operation is then described by a linear model at a range of observed operating points each identified by a set of parameters. As mentioned above, the innovation discloses measurements at the 48, 54, 60, 87, 98, and 99 percent maximum power settings. Over the frequency

range 50-250 Hz, the turbine exit signal will be the result of an attenuation of the input signal by an amount K. At the turbine exit, the input signal will also have a time delay since the indirect combustion noise travels at the flow velocity t.

Consider an input signal x(t) with a spectrum $G_{xx}(f)$ for a system with transfer function $H_{x,y}(f)$ and output signal y(t). Then the cross spectrum is given by Equation (12). For the turbofan engine **100**, the input to the turbine is the direct acoustic signal $x_d(t)$ and the time delayed entropy signal, $x_i(t)$, with a delay of τ_o. The entropy signal may represent in addition to a temperature fluctuation moving with the flow any other disturbance moving with the flow such as a vorticity fluctuation.

Referring back to FIG. **2**, as mentioned above, FIG. **2** illustrates a turbine-combustor-tailpipe noise system diagram **200** in accordance with an aspect of the innovation. The output turbine noise signals are $y_d(t)$ and $y_i(t)$. The output signal, y, is the sum of the direct combustion noise signal, y_d, and the indirect combustion noise signal, y_i:

$$y = y_d + y_i \qquad (18)$$

The direct combustion noise cross-spectral density, G_{xdyd}, is a product of the direct combustion noise turbine transfer function, $H_d(f)$, and the direct combustion noise input spectral density, G_{xd}.

$$G_{xdyd} = H_d(f) + G_{xd} \qquad (19)$$

The indirect combustion noise cross-spectral density, G_{xdyi}, is a product of the indirect combustion noise turbine transfer function, $H_i(f)$, the time delay factor, $e^{-j2\pi f\tau o}$, and the input indirect combustion noise spectral density, G_{xi}, which corresponds to an equivalent fluctuating entropy spectral density function.

$$G_{xdyi} = H_i(f) e^{-j2\pi f\tau o} \qquad (20)$$

The indirect combustion noise turbine transfer function, $H_i(f)$, is assumed to have a representation, H(f). The direct combustion noise turbine transfer function, $H_d(f)$, is assumed to have a representation, α H(f). Where α is a measure of the direct combustion noise to the indirect combustion noise. Thus:

$$H_d(f) = \alpha H(f) \qquad (21)$$

$$H_i(f) = H(f) \qquad (22)$$

The direct combustion noise and the entropy noise have the same origin in the combustion process. Consequently it is assumed that the input direct combustion noise spectral density and the input entropy fluctuation spectral density have the same form.

$$G_{xd} = G_{xi} \qquad (23)$$

Consequently, the measured cross-spectral density is given by:

$$G_{xdy} = G_{xdyd} + G_{xdyi} = H_d(F)G_{xd} + H_i(f)G_{xi} \qquad (24)$$

$$= H(f)(e^{-j2\pi f\tau o} + \alpha)G_{xd} = H_s(f)G_{xd}$$

For the frequency range of 50-250 Hz, α is negligible and H(f)=K where $\log_{10}$ (K)$\sim$−10. Consequently, the transfer function of the system is

$$H_s(f) = Ke^{-j2\pi f\tau o} \qquad (25)$$

The combustor entropy noise, and combustor hydrodynamic noise, N_d, are assumed independent of each other and independent of the tailpipe noise, N_T. Thus:

$$G_{NtNd} = G_{NiNT} = G_{NdNT} = 0 \qquad (26)$$

A linear curve fit covering the frequency range from 50-250 Hz was made to the cross spectrum phase angle for the measurement made using the combustor sensor **102** and both the first and second turbine exit sensor **104, 106**. Specifically, Table 2 illustrates the linear curve fit results based on the results from the combustor sensor **102** and the first turbine exit sensor **104**. Table 3 illustrates the linear curve fit results based on the results from the combustor sensor **102** and the second turbine exit sensor **106**.

TABLE 2

	Linear Fit Values			
Percent Maximum Power	a ms	b Degrees	Correlation	Std. Dev. ins
48	3.99	−78.06782	0.985	0.0701
54	3.86	−79.9248	0.982	0.0746
60	4.0229	−90.7813	0.974	0.0942
71	3.7079	−75.56375	0.97	0.093
87	3.4814	−83.738	0.948	0.117
98	3.99	−78.0678	0.985	0.07
99	3.3435	−83.024	0.944	0.117

TABLE 3

	Linear Fit Values			
Percent Maximum Power	a ms	b Degrees	Correlation	Std. Dev. ins
48	4.024	−77.3482	0.986	0.0687
54	4.079	−84.048	0.985	0.071
60	4.0664	−83.6347	0.986	0.0683
71	4.0188	−90.96	0.966	0.108
87	3.5794	−83.3152	0.961	0.104
98	3.5477	−88.01	0.958	0.107
99	3.57	270.46	0.966	0.096

The post-combustion residence time, t, expressed in ms, is determined from the slope of the linear curve fit expressed in Equation (27) below:

$$P = t(360/1000)f - Q \qquad (27)$$

or:

$$t = (P+Q)/(360/1000)f \qquad (28)$$

where P is the phase angle in degrees, Q is the intercept in degrees, and f is the frequency.

The post-combustion residence times are graphically shown in FIG. **17** for each power setting and microphone pair. The graph represented by the circles is for the combustion sensor **102** and the first turbine exit sensor **104**. Similarly, the graph represented by the triangles is for the combustion sensor **102** and the second turbine exit sensor **106**. The post-combustion residence time was measured as a function of engine power. For the example turbofan engine shown in FIG. **1**, the post-combustion residence time was approximately 4 ms at idle and 3.4 ms at a maximum power setting. As a result, the measurement of post-combustion residence time has implications for fuel usage and system fault detection.

The core noise components of the dual-spool turbofan engine were separated using coherence functions. A source location technique was used that adjusted the time delay between the combustor pressure sensor signal and the far-field microphone signal to maximize the coherence and

remove as much variation of the phase angle with frequency as possible. For a 130° far-field microphone, a 90.03 ms time shift worked best for the frequency band from 0-200 Hz, while an 86.98 ms time shift worked best for the frequency band from 200-400 Hz. Hence, the 0-200 Hz band signal took more time than the 200-400 Hz band signal to travel the same distance. This suggests the 0-200 Hz coherent cross spectral density band is partly due to indirect combustion noise attributed to entropy fluctuations, which travel at a low flow velocity in the combustor until interactions with the turbine pressure gradient produce indirect combustion noise. The signal in the 200-400 Hz frequency band is attributed mostly to direct combustion noise. The method disclosed herein is successful because acoustic and temperature fluctuations are related by a linear transfer function that includes a convective time delay. This experiment involved the measurements of pressure and temperature disturbances in a long tube connected to a combustor. This linear connection of entropy and pressure fluctuations implies the direct and indirect combustion noises are correlated at the source.

Referring to FIGS. **18** and **19**, a system **1800** and method **1900** of measuring the post-combustion residence time in a gas-turbine engine is described respectively in accordance with an aspect of the innovation. The system **1800** includes a measurement component **1810** comprised of the combustor sensor **102** and the first and second turbine exit sensors **104**, **106**, a receiving/calculation component **1820**, a tabulation component **1830**, and a computation component **1840**. The system **1800** processes information from the sensors described above to determine the post-combustion residence time in the gas-turbine engine, as will be subsequently described.

Specifically, at **1902**, the combustor sensor **102** is placed at the combustor entrance, and the first and second turbine exit sensors **104**, **106** are placed at the turbine exit, as described above in reference to FIG. **1**. At **1904**, the combustor sensor **102** measures the combustor pressure at the combustor entrance and the first and second turbine exit sensors **104**, **106** measure turbine exit pressures at the turbine exit. At **1906**, the cross-spectrum functions, specifically phase angle and coherence functions, are computed from the signals generated by the pressure sensors. Specifically, the receiving/calculation component **1810** receives the signals sent from the combustor sensor **102**, and the first and second turbine exit sensors **104**, **106**. Upon receipt of the signals, the receiving/calculation component **1810** calculates the cross-spectrum and coherence functions. At **1908**, a linear curve fit is made to the cross-spectrum phase angle over an appropriate frequency range as determined by the coherence function being greater than 0.1. Specifically, the tabulation component **1820** determines the linear curve fit and tabulates the linear curve fit results in a table, as illustrated in Tables 2 and 3 above. At **1910**, the tabulation component further calculates a slope of the linear curve fit. At **1912**, the computation component **1830** computes the post-combustion residence time, t, from the slope of the linear curve fit using the formula in Equation (28) above.

Referring now to FIG. **20**, a block diagram of a computer operable to execute the disclosed architecture is illustrated in accordance with an aspect of the innovation. In order to provide additional context for various aspects of the subject innovation, FIG. **20** and the following discussion are intended to provide a brief, general description of a suitable computing environment **2000** in which the various aspects of the innovation can be implemented. While the innovation has been described above in the general context of computer-executable instructions that may run on one or more computers,

those skilled in the art will recognize that the innovation also can be implemented in combination with other program modules and/or as a combination of hardware and software.

Generally, program modules include routines, programs, components, data structures, etc., that perform particular tasks or implement particular abstract data types. Moreover, those skilled in the art will appreciate that the inventive methods can be practiced with other computer system configurations, including single-processor or multiprocessor computer systems, minicomputers, mainframe computers, as well as personal computers, hand-held computing devices, microprocessor-based or programmable consumer electronics, and the like, each of which can be operatively coupled to one or more associated devices.

The illustrated aspects of the innovation may also be practiced in distributed computing environments where certain tasks are performed by remote processing devices that are linked through a communications network. In a distributed computing environment, program modules can be located in both local and remote memory storage devices.

A computer typically includes a variety of computer-readable media. Computer-readable media can be any available media that can be accessed by the computer and includes both volatile and nonvolatile media, removable and non-removable media. By way of example, and not limitation, computer-readable media can comprise computer storage media and communication media. Computer storage media includes both volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules or other data. Computer storage media includes, but is not limited to, RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disk (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by the computer.

Communication media typically embodies computer-readable instructions, data structures, program modules or other data in a modulated data signal such as a carrier wave or other transport mechanism, and includes any information delivery media. The term "modulated data signal" means a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal. By way of example, and not limitation, communication media includes wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, RF, infrared and other wireless media. Combinations of the any of the above should also be included within the scope of computer-readable media.

With reference again to FIG. **20**, the exemplary environment **2000** for implementing various aspects of the innovation includes a computer **2002**, the computer **2002** including a processing unit **2004**, a system memory **2006** and a system bus **2008**. The system bus **2008** couples system components including, but not limited to, the system memory **2006** to the processing unit **2004**. The processing unit **2004** can be any of various commercially available processors. Dual microprocessors and other multi-processor architectures may also be employed as the processing unit **2004**.

The system bus **2008** can be any of several types of bus structure that may further interconnect to a memory bus (with or without a memory controller), a peripheral bus, and a local bus using any of a variety of commercially available bus architectures. The system memory **2006** includes read-only memory (ROM) **2010** and random access memory (RAM)

2012. A basic input/output system (BIOS) is stored in a non-volatile memory 2010 such as ROM, EPROM, EEPROM, which BIOS contains the basic routines that help to transfer information between elements within the computer 2002, such as during start-up. The RAM 2012 can also include a high-speed RAM such as static RAM for caching data.

The computer 2002 further includes an internal hard disk drive (HDD) 2014 (e.g., EIDE, SATA), which internal hard disk drive 2014 may also be configured for external use in a suitable chassis (not shown), a magnetic floppy disk drive (FDD) 2016, (e.g., to read from or write to a removable diskette 2018) and an optical disk drive 2020, (e.g., reading a CD-ROM disk 2022 or, to read from or write to other high capacity optical media such as the DVD). The hard disk drive 2014, magnetic disk drive 2016 and optical disk drive 2020 can be connected to the system bus 2008 by a hard disk drive interface 2024, a magnetic disk drive interface 2026 and an optical drive interface 2028, respectively. The interface 2024 for external drive implementations includes at least one or both of Universal Serial Bus (USB) and IEEE 1394 interface technologies. Other external drive connection technologies are within contemplation of the subject innovation.

The drives and their associated computer-readable media provide nonvolatile storage of data, data structures, computer-executable instructions, and so forth. For the computer 2002, the drives and media accommodate the storage of any data in a suitable digital format. Although the description of computer-readable media above refers to a HDD, a removable magnetic diskette, and a removable optical media such as a CD or DVD, it should be appreciated by those skilled in the art that other types of media which are readable by a computer, such as zip drives, magnetic cassettes, flash memory cards, cartridges, and the like, may also be used in the exemplary operating environment, and further, that any such media may contain computer-executable instructions for performing the methods of the innovation.

A number of program modules can be stored in the drives and RAM 2012, including an operating system 2030, one or more application programs 2032, other program modules 2034 and program data 2036. All or portions of the operating system, applications, modules, and/or data can also be cached in the RAM 2012. It is appreciated that the innovation can be implemented with various commercially available operating systems or combinations of operating systems.

A user can enter commands and information into the computer 2002 through one or more wired/wireless input devices, e.g., a keyboard 2038 and a pointing device, such as a mouse 2040. Other input devices (not shown) may include a microphone, an IR remote control, a joystick, a game pad, a stylus pen, touch screen, or the like. These and other input devices are often connected to the processing unit 2004 through an input device interface 2042 that is coupled to the system bus 2008, but can be connected by other interfaces, such as a parallel port, an IEEE 1394 serial port, a game port, a USB port, an IR interface, etc.

A monitor 2044 or other type of display device is also connected to the system bus 2008 via an interface, such as a video adapter 2046. In addition to the monitor 2044, a computer typically includes other peripheral output devices (not shown), such as speakers, printers, etc.

The computer 2002 may operate in a networked environment using logical connections via wired and/or wireless communications to one or more remote computers, such as a remote computer(s) 2048. The remote computer(s) 2048 can be a workstation, a server computer, a router, a personal computer, portable computer, microprocessor-based entertainment appliance, a peer device or other common network

node, and typically includes many or all of the elements described relative to the computer 2002, although, for, purposes of brevity, only a memory/storage device 2050 is illustrated. The logical connections depicted include wired/wireless connectivity to a local area network (LAN) 2052 and/or larger networks, e.g., a wide area network (WAN) 2054. Such LAN and WAN networking environments are commonplace in offices and companies, and facilitate enterprise-wide computer networks, such as intranets, all of which may connect to a global communications network, e.g., the Internet.

When used in a LAN networking environment, the computer 2002 is connected to the local network 2052 through a wired and/or wireless communication network interface or adapter 2056. The adapter 2056 may facilitate wired or wireless communication to the LAN 2052, which may also include a wireless access point disposed thereon for communicating with the wireless adapter 2056.

When used in a WAN networking environment, the computer 2002 can include a modem 2058, or is connected to a communications server on the WAN 2054, or has other means for establishing communications over the WAN 2054, such as by way of the Internet. The modem 2058, which can be internal or external and a wired or wireless device, is connected to the system bus 2008 via the serial port interface 2042. In a networked environment, program modules depicted relative to the computer 2002, or portions thereof, can be stored in the remote memory/storage device 2050. It will be appreciated that the network connections shown are exemplary and other means of establishing a communications link between the computers can be used.

The computer 2002 is operable to communicate with any wireless devices or entities operatively disposed in wireless communication, e.g., a printer, scanner, desktop and/or portable computer, portable data assistant, communications satellite, any piece of equipment or location associated with a wirelessly detectable tag (e.g., a kiosk, news stand, restroom), and telephone. This includes at least Wi-Fi and Bluetooth™ wireless technologies. Thus, the communication can be a predefined structure as with a conventional network or simply an ad hoc communication between at least two devices.

Wi-Fi, or Wireless Fidelity, allows connection to the Internet from a couch at home, a bed in a hotel room, or a conference room at work, without wires. Wi-Fi is a wireless technology similar to that used in a cell phone that enables such devices, e.g., computers, to send and receive data indoors and out; anywhere within the range of a base station. Wi-Fi networks use radio technologies called IEEE 802.11 (a, b, g, etc.) to provide secure, reliable, fast wireless connectivity. A Wi-Fi network can be used to connect computers to each other, to the Internet, and to wired networks (which use IEEE 802.3 or Ethernet). Wi-Fi networks operate in the unlicensed 2.4 and 5 GHz radio bands, at an 11 Mbps (802.11a) or 54 Mbps (802.11b) data rate, for example, or with products that contain both bands (dual band), so the networks can provide real-world performance similar to the basic 10BaseT wired Ethernet networks used in many offices.

To summarize the formation of NO_x in gas-turbine combustors, NO_x is formed in a distributed zone manner and that higher temperature-rise combustors will be required as turbine materials improve. While most correlation of NO_x production equations apply in the primary zone, research has found equations for other zones. The innovation disclosed herein is based on a combustor/turbine system study and not on each component separately, which does not lead to these findings.

Others have indicated that using a constant thrust power setting a decrease in NO_x emissions as a function of engine

15   16

age is observable. This is attributed to an increase in mass flow due to hot section damage. It is suggested that turbine damage results in lower NO$_x$ emissions rate due to decreased residence time. Consequently, the post-combustion residence time measurement procedure disclosed herein may be utilized as a tool to detect turbine damage from aging or verify proper operation.

The typical fault diagnostic turbine system sensor system depends on measuring such items as fan exit pressure, LPC exit pressure, burner pressure, LPC exit temperature, HPC exit temperature, exhaust gas temperature, fuel flow, low spool speed, and high spool speed. None of these items convey the same information as the combustor residence time, which is a function of the turbine blade system operating condition and geometry. The available time to take corrective or compensatory actions such as repair or replace a part or reduce system operational loads to extend the life of the faulted part may be reduced with the additional information obtained from the innovation.

A gas turbine engine in a military or commercial aero-engine, or in industrial environment is a safety-critical system, which needs real-time fault detection and a decision support system to advise corrective actions so that the system can continue to function without jeopardizing the safety of personnel or damage to the equipment involved. Information on the status of the post-combustion residence time can provide additional information not available from any current sensor used in current fault detection systems.

Finally, in addition, jet fuel costs are 30 percent of an airlines cost. The status of post-combustion resident time as a function of time might provide information related to fuel usage.

What has been described above includes examples of the innovation. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the subject innovation, but one of ordinary skill in the art may recognize that many further combinations and permutations of the innovation are possible. Accordingly, the innovation is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims. Furthermore, to the extent that the term "includes" is used in either the detailed description or the claims, such term is intended to be inclusive in a manner similar to the term "comprising" as "comprising" is interpreted when employed as a transitional word in a claim.

What is claimed is:

1. A method of measuring a residence time in a gas-turbine engine:
   placing a plurality of pressure sensors at a combustor entrance and at a turbine exit of the gas-turbine engine;
   measuring a combustor pressure at the combustor entrance and a turbine exit pressure at the turbine exit;
   computing a plurality of cross-spectrum functions between a combustor pressure sensor signal from the measured combustor pressure and a turbine exit pressure sensor signal from the measured turbine exit pressure;
   applying a linear curve fit to the plurality of cross-spectrum functions; and
   computing a post-combustion residence time from the linear curve fit.

2. The method of claim 1, wherein prior to computing a post-combustion residence time from the linear curve fit, the method further comprising calculating a slope of the linear curve fit.

3. The method of claim 2, wherein the slope of the linear curve fit is a slope of the combustor pressure sensor signal and the turbine exit pressure sensor signal cross spectrum phase angle over a predetermined frequency range.

4. The method of claim 3, wherein the predetermined frequency range is 0-400 Hz.

5. The method of claim 4, wherein the combustor pressure sensor signal and the turbine exit pressure sensor signal is generated by indirect combustion noise.

6. The method of claim 1, wherein the plurality of cross-spectrum functions include a phase angle function and a coherence function.

7. The method of claim 1, wherein the plurality of pressure sensors includes a combustor pressure sensor disposed at a combustor entrance, a first turbine exit pressure sensor disposed at a first turbine exit, and a second turbine exit pressure sensor disposed at a second turbine exit.

8. The method of claim 7 further comprising calculating a slope of a cross spectrum phase angle over a predetermined frequency range from a combustor sensor pressure signal of the combustor pressure sensor and a first turbine exit sensor pressure signal of the first turbine exit pressure sensor or a second turbine exit sensor pressure signal of the second turbine exit pressure sensor.

9. A system to measure a post-combustion residence time in a gas-turbine engine comprising:
   a measurement component that measures a plurality of combustion and/or turbine flow pressures in the engine;
   a receiving/calculation component that calculates a plurality of cross-spectrum functions based on the measured plurality of combustion and/or turbine flow pressures;
   a tabulation component that tabulates a linear curve fit based on the calculated plurality of the cross-spectrum functions; and
   a computation component that computes the post-combustion residence time in the gas-turbine engine.

10. The system of claim 9, wherein the plurality of cross-spectrum functions include a phase angle function and a coherence function.

11. The system of claim 9, wherein the tabulation component further calculates a slope of the linear curve fit.

12. The system of claim 11, wherein the slope of the linear curve fit is a slope of a combustor pressure sensor signal from the measurement component and a turbine exit pressure sensor signal from the measurement component cross spectrum phase angle over a predetermined frequency range of 0-400 Hz.

13. The system of claim 12, wherein the combustor pressure sensor signal and the turbine exit pressure sensor signal is generated by indirect combustion noise.

14. The system of claim 9, wherein the measurement component includes a combustor pressure sensor disposed at a combustor entrance, a first turbine exit pressure sensor disposed at a first turbine exit, and a second turbine exit pressure sensor disposed at a second turbine exit.

15. The system of claim 14, wherein the tabulation component calculates a slope of a combustor sensor pressure signal from the combustor pressure sensor and a first turbine exit sensor pressure signal from the first turbine exit pressure sensor or a second turbine exit sensor pressure signal from the second turbine exit pressure sensor cross spectrum phase angle over a predetermined frequency range.

16. A method of measuring a residence time in a gas-turbine engine comprising:
   placing a plurality of pressure sensors at a combustor entrance and at a turbine exit of the gas-turbine engine;
   measuring an indirect combustion noise of the gas-turbine engine;

computing a phase angle function and a coherence function of the indirect combustion noise;

applying a linear curve fit to the plurality of cross-spectrum functions; and

computing a post-combustion residence time from the linear curve fit.

17. The method of claim **16**, wherein prior to computing a post-combustion residence time from the linear curve fit, the method further comprising calculating a slope of the linear curve fit.

18. The method of claim **17**, wherein the slope of the linear curve fit is a slope of the combustor pressure sensor signal and the turbine exit pressure sensor signal cross spectrum phase angle over a predetermined frequency range.

19. The method of claim **16**, wherein measuring the indirect combustion noise includes measuring a combustor pressure at the combustor entrance and a turbine exit pressure at the turbine exit.

20. The method of claim **16**, wherein the plurality of pressure sensors includes a combustor pressure sensor disposed at a combustor entrance, a first turbine exit pressure sensor disposed at a first turbine exit, and a second turbine exit pressure sensor disposed at a second turbine exit.

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